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"A lithostratigraphic and genetic study of Quaternary sediments in the vicinity of Medicine Hat, Alberta"

by

David N. Proudfoot

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

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OF Doctor of Philosophy

Department of Geology

EDMONTON, ALBERTA

Fall 1985

THE UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled "A lithostratigraphic and genetic study of Quaternary sediments in the vicinity of Medicine Hat, Alberta" submitted by David N. Proudfoot in partial fulfilment of the requirements for the degree of Doctor of Philosophy.

Abstract

The Medicine Hat area of southeastern Alberta contains some of the most complete exposures of Quaternary sediment in the Plains region of North America. It is also well known for the wealth of fossil material interpreted by other workers to represent fauna that lived during preglacial and interglacial times. This study was conceived to take advantage of these factors in order to develop a lithostratigraphic framework for Pleistocene sediment in the area so that the stratigraphic sequence and chronology could be correlated with adjacent areas.

The similarity in diamicton grain-size distribution, clay mineralogy, and coarse sand lithology examined within this study do not allow subdivision and correlation of stratigraphic units. A study of lithofacies, however, in particular diamicton, and delineation of a major unconformity, provided a solution. This involved the development of a lithofacies classification that centeres around diamicton and associated lithofacies. The classification is based primarily on the presence or absence of layering, stratification or unlithified inclusions. The six most important lithofacies in this classification include: (i) unlayered diamicton (subglacially deposited); (ii) stratified diamicton (more han 80 percent diamicton with thin interbeds of sand and silt) deposited by debris-flows, underflows, and by rain out; (iii) diamicton containing lenses (more than 70 percent diamicton that contains large sand and silt lenses) deposited from a supraglacial position by melting out; (iv) deformed stratified diamicton formed by injection of sediment and collapse as buried ice melted out; (v) layered diamicton (composed of highly attenuated layers) formed by subglacial molding, melting out and lodgement; (vi) interbedded diamicton, sand, and silt (less than 80 percent diamicton with thick beds of sand and silt) deposited proglacially by subaquatic slumps, debris-flows and density underflows.

The lithostratigraphic framework includes four formations. The oldest is the Empress Formation, which contains three members. The lower member is fluvial quartzitic sand and gravel containing material derived from the Canadian Shield and is of preglacial age. It is sharply overlain by fluvial silty clay and sand of the middle member. The upper member is a fining upward sequence of sand and silt topped by silt and clay rhythmites, which was deposited in a proglacial lake that formed as an advancing glacier (the beginning of the Phase One Glaciation) blocked regional drainage. Till of formation A containing

granitic and mafic rocks derived from the Canadian Shield overlies these rhythmites. It has a predominantly subglacial origin. Formation A is unconformably overlain by a gravel fluvial lag and sand of the lower member of formation B. The middle member is likely an interglacial or interstadial deposit. Where this member gradationally overlies the lower member, sandy silt occurs in channels that are incised into the top of formation A. Elsewhere, it is composed predominantly of layered and stratified diamicton that sharply overlies the lower member. This member is interpreted as proglacial lake sediment and represents the beginning of the Phase Two glaciation. It was overridden by a glacier that deposited the upper member of formation B, unlayered diamicton, subglacially. As the Phase Two deglaciation occurred, diamicton containing lenses was deposited from the top of the basal debris zone. Thin silt and clay rhythmite beds form the base of formation C, which overlies formation B. They were deposited in a short-lived proglacial lake. Subsequently, sand, silt and diamicton of formation C were deposited during postglacial and Holocene time.

Acknowledgements

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My fieldwork was ably assisted by Grant Carnie, Tim Dwyer, Don Mills, Paul Mortensen and Elaine Wierzbicki. Peter (Bim) Waters wrote most of the computer program that enables the digitizing of the orientation of elongate grains from thin section and Dr. H. Charlesworth kindly provided his ORIENT computer package for the analysis of orientation data. Throughout this study I have appreciated discussion and encouragement from Dr. A. M. Stalker who also provided testhole and geophysical logs and sample analyses for some of the holes. My fellow graduate students in the Quaternary Research Group provided many hours of stimulating and helpful discussion. In particular, I would like to thank Peter Bobrowsky, Norm Catto and Dave Liverman for reading the first draft of this thesis. Jenni Blaxley entered part of the text into the computer and provided friendship in time of need. Many thanks to Dr. Gordon Williams for his friendship and support throughout this work.

Finally, I would like to thank Rochelle Allison who entered the bibliography, helped to put together the final draft and above all was my friend and companion, helping to maintain my sanity during the writing and final thesis preparations.

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I. INTRODUCTION

The Medicine Hat area (Figure 1.1) contains some extremely well exposed sequences of Quaternary sediment that occur in cliffs along about 32 km of the South Saskatchewan River valley. The primary area of study is approximately 130 km^2 (Figure 1.2) . It was chosen for detailed stratigraphic and sedimentological study because of its wealth of fossil and other organic material. Many of these outcrops have been studied in the past from a biostratigraphic and chronostratigraphic perspective that has provided a stratigraphic framework, based on radiocarbon dates and abundant fossils. for the glaciated parts of the Plains of western North America (Stalker, 1969a, 1970, 1972, 1976a, 1977b; Stalker and Churcher, 1970, 1972; Szabo *et al.*, 1973). However, detailed lithostratigraphic studies have not been carried out, so that correlation of this sequence with other sparsaley fossiliferous, non-fossiliferous, and non-organic bearing Quaternary sequences is tenuous.

Objectives of Study

1. To develop a Quaternary lithostratigraphic framework based primarily on outcrop study, that utilizes the physical characteristics of sediments and their lithofacies relationships.
2. To identify and map diamicton and associated lithofacies to aid in stratigraphic unit delineation and correlation.
3. To determine typical lithofacies sequences.
4. To interpret the genesis of each lithofacies using the techniques of process sedimentology and modern analogs where possible.

Location and Physiography

The study area is located in southeastern Alberta, bordering the South Saskatchewan River from the vicinity of Redcliff in the west to just north of Medicine Hat in the east (Figure 1.2). It is located entirely within the Interior Plains physiographic region (Figure 1.3), comprising primarily flat to gently undulating terrain, with local topographic highs provided by hummocky moraine complexes that rise as much as 15 metres above adjacent terrain. Topographic lows are dominated by the valley of the South Saskatchewan

Figure 1.1. Location of the study area.

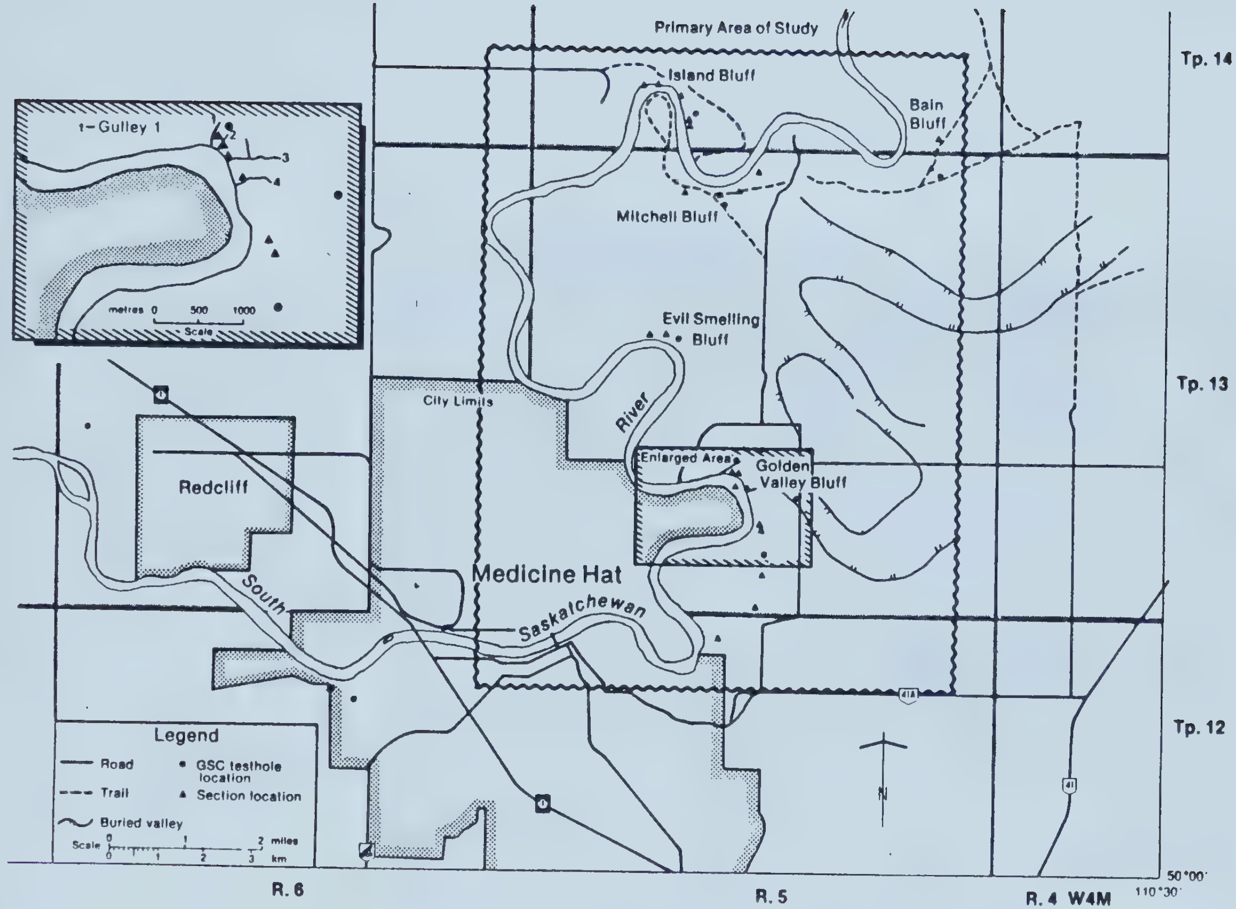

Figure 1.2. Detailed map of the study area showing the location and name of the sections examined and the location of measured sites and testholes.

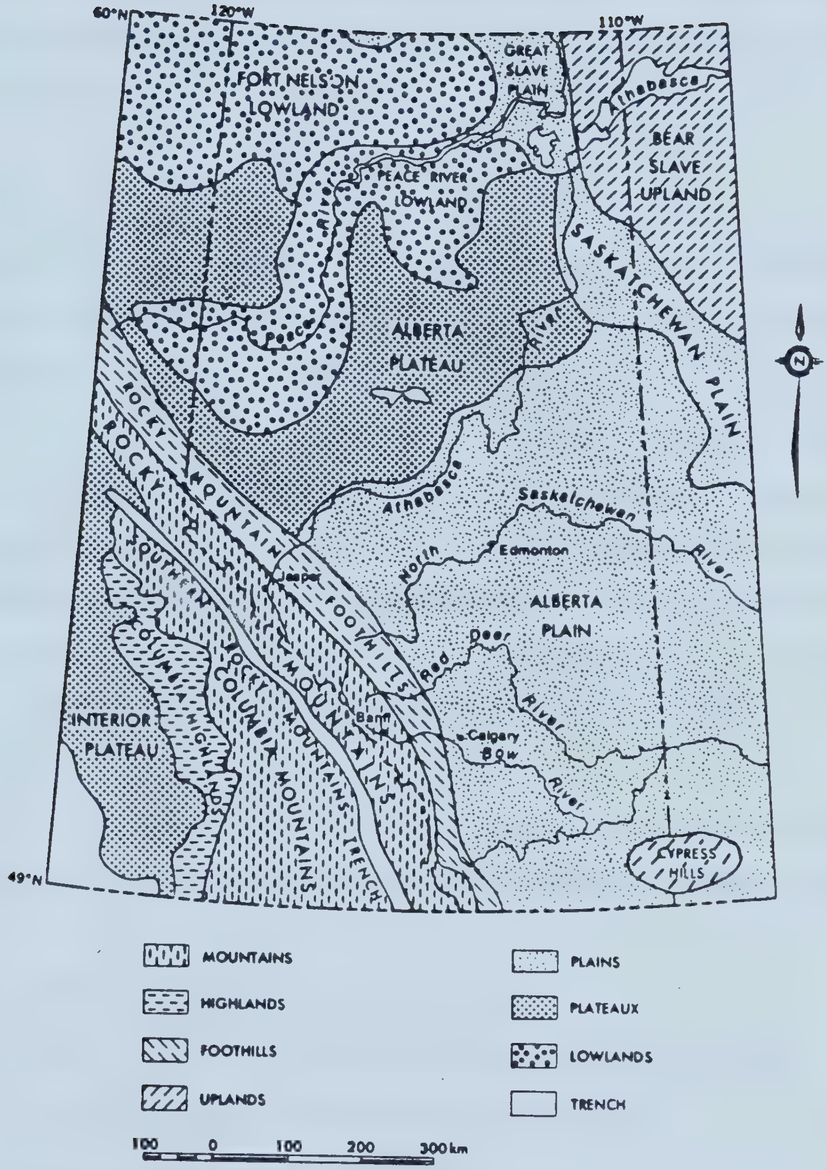

Figure 1.3. The physiographic regions of Alberta (after Acton and Crosson, 1978).

River which varies from about 50 to 100 metres deep and from 800 to 3000 metres wide. Its course generally meanders where it incises thick sequences of Quaternary sediment and forms much straighter reaches where it cuts into bedrock terrain. Other topographic lows are formed by glacial meltwater channels now dry and occupied by small misfit streams. These coulees, as they are known locally, can be as deep and broad as the present drainage system.

Bedrock Geology

The valley of the South Saskatchewan River and various coulees cut through the blanket of Quaternary sediment to expose the underlying upper Cretaceous bedrock. Two formations are known to crop out directly under this cover (Table 1.1). The oldest, the Foremost Formation, consists of grey and light brown argillaceous sandstone, buff coloured hard sandstone, grey siltstone, and green and grey shale with ironstone bands and coal. It is exposed only in the modern valley of the South Saskatchewan River (Irish, 1968). The Oldman Formation, which overlies the Foremost Formation, consists of green and light grey shale and silty shale and grey argillaceous sandstone, hard calcareous sandstone, and discontinuous ironstone beds, and it forms the surface bedrock unit away from the river valley.

The bedrock in the nearby area and across hundreds of kilometres in all directions has three characteristics that likely contributed to glacial behaviour and glacial sediment character.

(1) The bedrock is relatively unindurated and therefore soft.

(2) The bedrock is composed of beds of substantially different permeabilities.

(3) Bedding in the bedrock is undeformed and essentially flat lying.

Bedrock Topography

The surface elevation of the top of the Cretaceous bedrock that underlies the study area was mapped by Westgate (1968) and Carlson (1970) from borehole data. Most of this surface is believed to be equivalent to the preglacial landscape, although interglacial rivers may also have eroded channels into bedrock (Fig. 1.4). This preglacial terrain is dominated by broad, mature valleys that are up to tens of kilometres wide and 125 m

Upper Cretaceous	Bearpaw Formation	dark brown, sandy shale; dark gray shale; argillaceous sandstone; ironstone concretionary bands; bentonite (marine)
	Oldman Formation	gray shale; dark gray carbonaceous shale; gray and dark gray siltstone; gray and light gray sandstone; thin limestone beds; ironstone bands; coal seams (non-marine)
	Foremost Formation	green and gray shale; carbonaceous shale; gray siltstone; gray and pale brown sandstone; ironstone bands; coal seams (non-marine)

Table 1.1. Near surface rock stratigraphic units in the Medicine Hat area (after Irish, 1968)

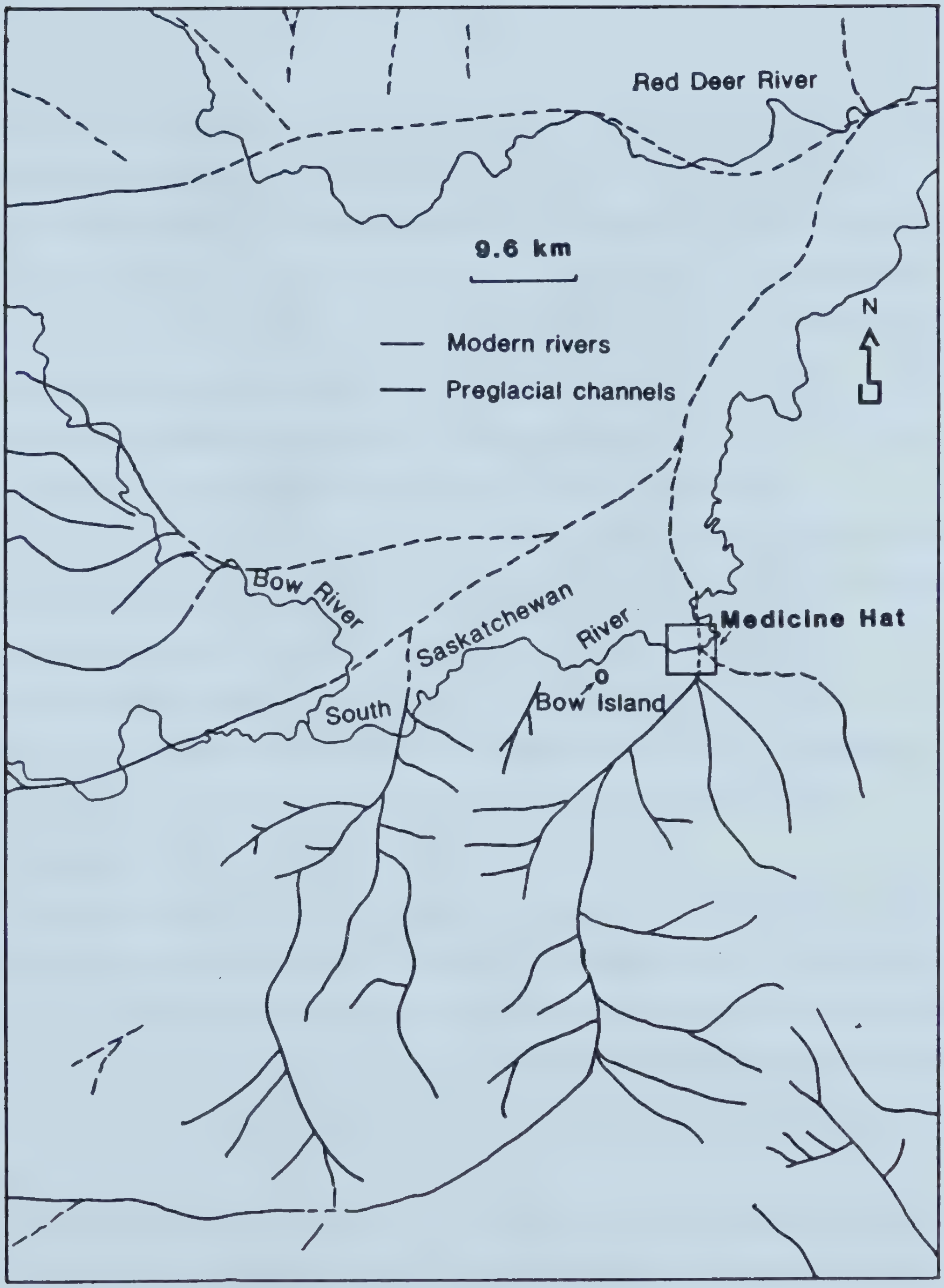

Figure 1.4. Main preglacial valley and divide locations for southern Alberta (after Geiger, 1972).

deep, with many smaller tributary valleys and moderately dissected interfluvial areas. Drainage was generally to the northeast parallel to the regional surface slope.

Previous Work

Many workers have studied various aspects of the preglacial and glacial landscape and the associated sediments in the Medicine Hat area. G.M. Dawson (1885), R.G. McConnell (1885, 1886), and Dawson and McConnell (1895) were the first to document the regional physiography and geology. McConnell (1886) specifically mentions the outcrops in the study area northeast of Medicine Hat. Johnston and Wickenden (1931) reported on moraines and glacial lakes in southern Saskatchewan and southern Alberta, and Horberg (1952, 1954) documented the glacial geomorphology, drift lithologies and Pleistocene stratigraphy for an area about 90 km west of Medicine Hat.

In 1968, Westgate compiled his 1:250 000 scale surficial geology map and report of the Foremost-Cypress Hills area which encompasses the area just south of Medicine Hat and extends west to include the Bow Island area (Fig. 1.1). He interpreted five Laurentide glacial advances into the area based on geomorphology -- primarily end moraines and associated meltwater channel drainage relationships -- and defined five corresponding morphostratigraphic drift sheets. However, he did not define rock-stratigraphic units for the glacial sediment.

Berg and McPherson (1972) compiled the Medicine Hat 1:250 000 surficial geology map, which adjoins the north boundary of Westgate's map, thus completing the mapping of surficial geology in the study area. They recognized "at least three till sheets in the area", and noted that the best exposures were along the South Saskatchewan River valley north of Medicine Hat. No attempt was made to interpret a Quaternary stratigraphy or history.

Shetsen (1984) has produced a 1:1 000 000 scale surficial geology map for southeastern Alberta (Figure 1.5) that provides a synthesis of glacial landforms and sediment distribution over a very large area. This map, combined with a regional study now in progress, documents the former existence of several Keewatin[1] prairie ice lobes or

----

[1]The term Keewatin as used here refers to a major ice lobe that advanced from the District of Keewatin, Northwest Territories, on the west side of Hudson Bay, to cover the Western Plains of Canada (Shilts, 1979).

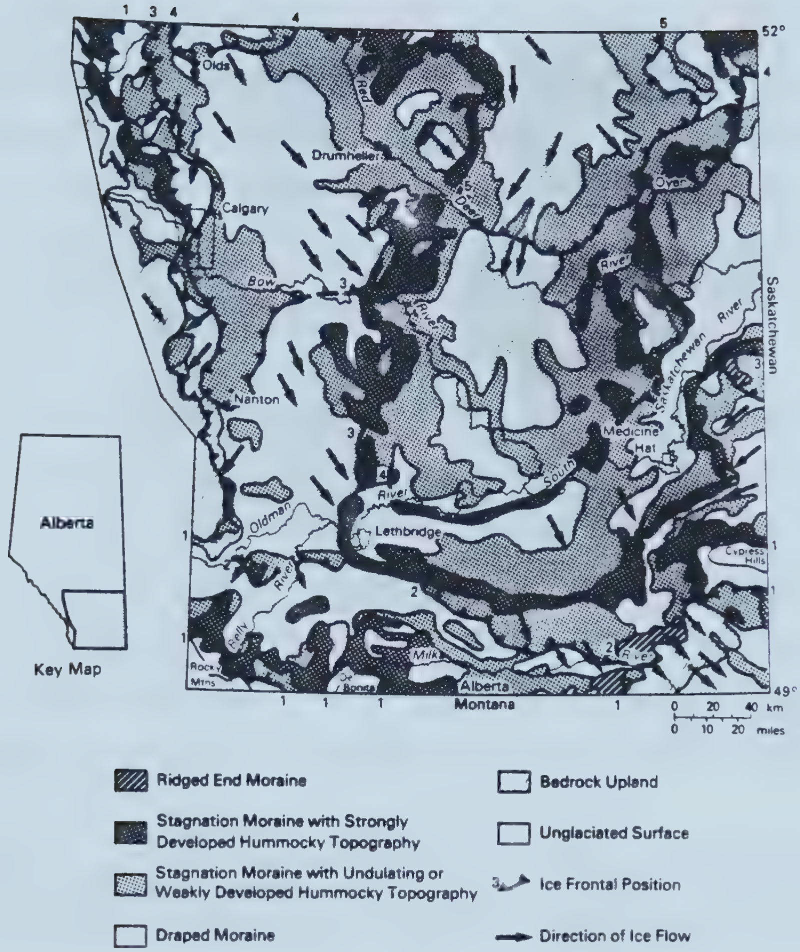

Figure 1.5. Location and generalized glacial geomorphology of southern Alberta (Shetsen, 1984).

streams that Shetsen interprets as having advanced during the late Wisconsin.

The major contributor to the study of the surficial geology, Quaternary stratigraphy and history of southern Alberta has been by Stalker, who has worked in the area since the mid 1950s (Stalker, 1969a, 1972, 1976, 1983; and Stalker and Churcher, 1970, 1972, 1982). Although he did not map the surficial geology of the Medicine Hat area, he determined a Quaternary stratigraphy for the area from outcrop study. Stalker's proposed stratigraphy includes a series of preglacial, glacial and interglacial periods defined primarily on the basis of till-unit correlation, radiocarbon dates, and paleontological data. It is important to note, however, that sedimentology and quantitative physical properties of the Quaternary deposits were not considered in the formulation of his stratigraphy.

The first documented attempts to differentiate glacial sediments of probable different provenance in southern Alberta by other than geomorphic or field relationships were by M. Rutulis (1962) and P. Vernon (1962), working in the Lethbridge area. Vernon concluded that till fabric could be used to correlate, but that other lithological characteristics including pebble lithology varied according to local bedrock and glacier provenance and could not be used to correlate beds. Rutulis concluded that till-pebble lithology provided the best method for distinguishing till units in the two sections that he studied.

Later Barendregt (1977) and Catto (1981) differentiated surface till units in southeastern Alberta on the basis of physical properties. Both of these workers were restricted to near-surface exposures and so were unable to develop correlations for glacial sediment below the surface.

Sources of Data

Unanalyzed sidewall samples, granulometric and carbonate analyses of some sidewall samples, testhole lithologs, and geophysical logs for 1969 and 1973 testholes were provided by A. MacS. Stalker of the Geological Survey of Canada. All section data were obtained by the author during the summers of 1978 to 1982.

A. Definition of the problem

Introduction

In a paper that discussed Quaternary stratigraphy in southern Alberta and southwestern Saskatchewan, Stalker (1976a: 402) stated:

> ...the little that is presented about integration of the sequences west of Lethbridge with those already described for Medicine Hat is highly speculative, for there are few Wisconsin or older ash or vertebrate sites known from west of Lethbridge to aid the correlation and none of the beds there can be traced directly to Medicine Hat.

This quotation and encouragement from Stalker and others led the author to the current study which attempts to establish a stratigraphic framework for Pleistocene sediment in the Medicine Hat area based on their physical characteristics and sedimentology.

Much research dealing with glacial sediment has recently been published. This has been complimented by detailed study of the dynamics of modern glaciers and their deposits. Research on the genesis of ancient glacial deposits commonly relate to limited, isolated, but well exposed outcrops that have been sampled and analyzed in great detail. Very few attempts have been made to analyze several sections sedimentologically within a stratigraphic context, to determine recognizable, mappable characteristics that can be regionally correlated. In part this is due to the fact that many glacial geologists are concerned with mapping surface materials and geomorphology, with their prime objective being to produce a map and a geologic history.

The understanding of glacial environments and glacial sediments is in its infancy, compared to other sedimentary environments such as the fluvial system. Much has been said and written about "till genesis" and the classification of kinds of till but little attempt has been made to systematically describe these sediments in such a way as to make genetic interpretations more consistent (Eyles *et al.*, 1983). Researchers with a sedimentological perspective have made some progress in this general area, but because they lacked the stratigraphic background, have not usually extended their studies regionally.

The Problem

A cursory look at any one of the major outcrops in the Medicine Hat area reveals multiple stratigraphic units. Closer examination reveals two or more layers of diamicton that appear different in colour and structure. The problem considered here is whether these differences can be recorded and in some way quantified to allow the correlation of units between outcrops and to aid in determining the genesis of the units and interpreting of the Quaternary geological history.

The Approach

Diamicton was selected for detailed examination because it is the predominant sediment type. Without diamicton, it is generally not possible to correlate between outcrops because other lithologic types are discontinuous. For practical purposes, the study progressed on an individual-outcrop basis, first correlating along a single outcrop, using laboratory results to support visual field correlations, and then using all of these characteristics to correlate between outcrops. Lithologs from testholes adjacent to important exposures were used as a check for possible outcrop disruption and to provide data for the complete sequence at one site, eliminating the need to form composite sequences (as was required for most sections). It was apparent, in the field, that few sections contained the complete Quaternary record. For example, at Golden Valley Bluff (Figure 1.2 and Plate 1.1), six units were recognized, whereas at Island Bluff (Figure 1.2, Plate 1.2), 55 km away in the same river valley, twelve units were identified. In particular, four diamicton units were mapped at the former locality and seven at the latter.

Results of laboratory analysis and careful field measurement and description did not resolve the problem of correlation. Using the traditional interpretation for diamicton in this region, it was not obvious if any of the additional diamicton units at Island Bluff were deposits of glaciations that for some reason did not leave any evidence of their presence at Golden Valley Bluff (Fig. 1.2). The possibility that several lithofacies within one unit could represent one glacial event or several nonglacial events then became an hypothesis.

Following the guidelines to lithofacies definition as determined by Walker (1979), outcrops were re-examined and lithofacies were delineated (Table 1.2). These lithofacies were defined on the basis of structural and lithological aspects, with no genetic

Plate 1.1. The central portion of Golden Valley Bluff. Formations are labelled as follows: Fm., formation; UB, upper member of formation B; MB middle member of formation B.

Plate 1.2. Multiple diamicton exposure at Island Bluff. Interbedded diamicton (d) and silty sand (ss) mark the middle member of formation B. The base of this member occurs at the top of the grassy slope on the left. It is underlain by diamicton of formation A (exposed on the right side of the photograph).

Table 1.2. List of major lithofacies in the Medicine Hat area

Diamicton		
Unlayered	MD	
Stratified	SD	
laminated		-L
Diamicton containing lenses	DCL	
Deformed stratified	DSD	
Layered	LD	
Interbedded sand, silt, and diamicton	ISSD	
tabular		-T
lenticular		-L
Undifferentiated	U	
Intermittent clast alignments		
Discontinuous thin-bedded gravel band		
Thick-bedded gravel		
Cross-bedded sand		
Interlaminated silt and clay		
Thick bedded silt		
Laminated silt		
Massive pebbly silt		

interpretation attached. Later, when lateral and vertical associations between lithofacies were studied, commonly from composite section descriptions and laboratory data, lithofacies subdivision or combination was performed. After most outcrops in the study area had been examined, and pertinent literature on processes and possible modern analogs reviewed, a genetic interpretation for each lithofacies at each locality was made. At the same time, it was possible to develop a stratigraphic framework and to make correlations (Table 1.3).

B. Methodology

Introduction

This section outlines the various field and laboratory techniques used. The general approach involved the use of published and unpublished data, drillhole data, and surficial geology maps as an aid in the development of a field program. Sections were then mapped and sampled with particular attention given to the sedimentary characteristics of each unit. Lithofacies were delineated and described for all deposits in the area. Orientation data and oriented diamicton samples were collected and analyzed to document lithofacies clast orientations and to provide data for genetic interpretation. A field-based stratigraphic framework was developed and subsequently tested using the texture, coarse-sand lithology, and clay mineralogy of diamicton units. Refinements and further detail were based on the fit of these data to the stratigraphic framework.

Lithofacies mapping

The term *lithofacies* as used here refers to a set of characteristics based on the total field aspect of the deposit being classified. It is an objective definition that uses lithological and structural aspects detected in the field (Walker, 1979: 1). If correlations are to be based on diamicton, then we must observe its lateral and vertical continuity. This consideration has directed a major effort within this study to recognize, define, and map diamicton and related lithofacies. The recognition and mapping of diamicton lithofacies is arbitrary, because lithofacies grade into one another both laterally and vertically. Many diamictons appear complex, with a variety of juxtaposed structures, whereas others

ROCK STRATIGRAPHY		LITHOLOGY
FORMATION C		silt and clay rhythmites; massive silt containing paleosols; interbedded sand, silt and diamicton
FORMATION B	upper member	diamicton
	middle member	sand, silt and diamicton
	lower member	sand and gravel (wood)
FORMATION A		diamicton
EMPRESS FORMATION	upper member	silt and clay
	middle member	sand, silt and clay (wood)
	lower member	sand and gravel
BEDROCK		sandstone, siltstone, shale, ironstone and coal

Table 1.3. Summary of rock stratigraphy and lithology for the Medicine Hat area

appear simple due to the apparent absence of structure. During the development of a lithofacies classification, a number of problems arise. What structures are important? Are there logical structural associations? What is the nature of contacts within and between diamicton beds? How does one evaluate postdepositional deformation? These questions are addressed in the description of lithofacies.

Fieldwork

Outcrops were identified from aerial photographs, literature, and from a canoe reconnaissance along the South Saskatchewan River. Five outcrops were selected for detailed study on the basis of size and quality of exposure. The field program involved section sketching, panoramic photography, section measurement, and sampling. Most cliff access was gained along narrow gullies that dissect cliff faces and from the top of scree slopes and slump blocks adjacent to cliff faces. Where high nearly vertical exposures could not be approached, they were studied through binoculars.

The variation in the number of diamicton units between outcrops and the great variation of diamicton characteristics prompted the development of a lithofacies classification (see Chapter II). A preliminary stratigraphic sequence for each outcrop was developed based on several stations along the exposure. Tentative correlation between outcrops was based on the physical characteristics of units and their stratigraphic position compared with the stratigraphic sequence recognized at the most complete exposure (centre of Golden Valley Bluff, DNP78-13, Plate 1.1), designated as the reference section.

Sampling and Analysis

For the diamicton portion of each sequence measured, a minimum of three samples were taken for each recognizeable lithofacies, with a maximum vertical sample interval of 1 metre. Where possible the outcrop was cleaned to expose relatively fresh material at each sample site. Sample sites close to inclusions or strata of sand, silt, or clay were avoided, although separate samples of these inclusions or strata were commonly taken in addition to the diamicton samples.

In the laboratory, diamicton samples were disaggregated and sieved, with the less-than-1-mm fraction analyzed for size by hydrometer (ASTM technique, 1964) and the

1-to-2 mm and 2-to-4 mm fractions weighed and saved. The clay fraction was collected by centrifuging from suspension using the standard techniques used by the Alberta Geological Survey Sedimentology Laboratory. Clay slide preparation and clay mineralogy analysis followed the basic technique described by Johns *et al.* (1954). Two clay slides were prepared for each sample using the smear technique. One was then glycolated to expand mixed layer clays and the other heated to collapse them before X-ray diffraction. Semi-quantitative analysis of the clay mineralogy was performed using the peak height method outlined by Johns *et al.* (1954) using Bradley form factors.

The 1-to-2-mm sand fraction of selected diamicton samples and sand and gravel samples were first stained with alizarin red dye to aid in distinguishing limestone from dolostone and then analyzed under a binocular microscope. Lithological categories were developed on the basis of major rock types present. For each sample all grains were counted unless significantly more than 300 grains were present, in which case the sample was split using a sample splitter before one of the aliquots was counted.

Orientation data were measured using a Brunton compass from outcrops for a number of different linear features. These included scratched and polished surfaces, fold axes, and fault-plane orientations. In addition, a limited number of diamicton pebble fabrics were measured in the manner outlined by Harrison (1957b), with a minimum long to short clast axis ratio of 3:2. Most of the diamicton outcrops studied were too hard to allow easy excavation and removal of pebbles and contained so few of them that pebble fabric measurements proved to be too time consuming. In these locations, oriented blocks of diamicton 200 to 500 cm^3 were cut with a hacksaw, and their upper horizontal surface marked by a north arrow. In the laboratory, the oriented blocks were impregnated with Epoxy 330 or Epotek 301 that was dyed with Oracet Blue 2R dye. Thin sections were then cut from the blocks, parallel to the horizontal plane. A technique was developed to project the thin section image onto paper using a Carl Zeiss Jena Projection microscope under nine-power magnification so that the long axis of all elongated grains with long to short axis ratios of greater than 3:2 could be traced onto the paper along with the north arrow and a 1-cm-bar scale. The size of the particles measured ranged from 0.1 to 6 mm and as many measurements as possible were made from each thin section to avoid sample biasing. The number of measurements for each thin section ranged from approximately 75

to 550, according to the number of coarse grains in the sample, with an average of about 200.

The resulting grain long-axis map was then digitized on a Summagraphics Bit Pad. The digitizing program, which was developed by the author in conjunction with P. M. Waters (University of Alberta, 1981) for this study, automatically calculates the orientation and length of each long axis and places it in a file for future processing. Orientation data were then processed using the ORIENT package available at the Geology Department, University of Alberta (H.A.K. Charlesworth) to produce rose diagrams.

II. DESCRIPTION OF DEFORMATION STRUCTURES AND LITHOFACIES

A. Introduction

This chapter documents the sedimentary lithofacies and glacigenic deformation structures recognized in the study area. Deformation structures that are not attributable to soft-sediment deformation are associated with some lithofacies or sequence of lithofacies (Table 2.1) and are presented first. Subsequently, in the lithofacies descriptions, emphasis is placed on diamicton and closely associated lithofacies, because they are the dominant and most laterally extensive sediments in the Pleistocene sequence (Table 2.2). Other commonly recognized lithofacies are not described until the discussion of stratigraphic interpretation (chapter V) because (1) their genesis is understood and generally accepted, (2) they have been widely recognized by other workers, and (3) a more detailed description and interpretation does not add substantially to the objectives of this study.

As noted previously, if correlations are to be based on diamicton, then its lateral and vertical continuity must be observed. Thus, a major portion of this study is directed towards recognition, definition and mapping of diamicton and related lithofacies.

Due to time constraints, a practical limit was placed on the amount of detail that could be recorded in the field. This resulted in amalgamation of microfacies data. Furthermore, at many sites, outcrops were too dry for optimal recognition of subtle changes in colour and texture. Consequently, microstructures may not have been observed everywhere. Appendix A contains specific details of the sites referred to in the text.

B. Terminology

Diamicton as used in this study, refers to "any nonsorted or poorly-sorted sediment that contains a wide range of particle sizes" (Dreimanis, 1982a).

Clast refers to pebble- to boulder-sized coherent material.

Microclast refers to silt to grit-sized particles.

Microfabric refers to two-dimensional microclast orientation measured on thin sections.

Table 2.1. List of deformation structure terminology used in this paper

Large-scale Deformation Structures (affect more than one lithofacies)

- Folds
  - overturned (Plate 2.1)
  - synformal (Plate 2.2)
- Faults
  - low angle

Small-scale Deformation Structures (affect one lithofacies)

- Folds
  - overturned
  - isoclinal
  - asymmetrical (Plate 2.3)
- Faults
  - normal
  - low angle
- Fractures
  - zones (Plate 2.5)
  - planes
    - horizontal (Plate 2.4)
    - arcuate
- Attenuated structures
  - smears
  - smudges

Lithofacies	Diagnostic characteristics	Other Important Characteristics	Nature of Facies Contacts	Maximum Observed Thickness	Microclast Orientation	Lateral Extent
Unlayered Diamicton (UD)	no visible internal structure; composed of > 98 % diamicton	contains complete range of clast sizes from pebbles to boulders; contains few small undeformed sand and silt lenses (< 20 cm by 5 cm) in primary orientation; may contain small attenuated bands (< 1cm by 5 cm) of clay and silt adjacent to sharp basal contacts	drag folds and scratches along sharp basal; gradational upper	7 m	broad uni-modal to polymodal	100's of m
Stratified Diamicton (SD)	interbedded diamicton, sand, and silt; diamicton forms about 80 to 98 % of the deposit; stratification is parallel, undeformed surfaces; diamicton beds range from 1 to 100 cm thick sand and silt beds range from 0.1 to 10 mm thick	internal primary structures such as horizontal & cross-bedding are common in sandy strata; absence of sand and silt lenses; contains less large pebbles and cobbles than other lithofacies; rounded soft sediment clasts ; pebble- and cobble-sized clasts may be enveloped by over- and underlying stratification	sharp basal and gradational upper	7 m	broad bimod-al to poly-modal	100's of m
	Laminated component diamicton beds are internally laminated with gradational interlaminae contacts; diamicton beds range from 1 to 20 cm thick	normal grading in some silty sand beds; pebble- and cobble-sized clasts may be enveloped by over- and underlying stratification	sharp basal contact with small scale relief (< 0.3 cm); gradational upper	4 m		
Diamicton containing lenses (DCL)	composed of 70 to 90 % diamicton, with 10 to 30 % by volume sand and silt lenses that range up to 2 by 3 m in size	internal deformation of lenses is common; contains a complete range of clast sizes from small pebbles to boulders	gradational upper and lower	6 m	no preferred orientation	100's of m
Deformed stratified Diamicton (DSD)	composed of > 85 % diamicton that consists of discontinuous deformed beds of silty clay diamicton, sandy silt diamicton, and sand and silt deformation resembles soft-sediment deformation structures (injection, load); beds range from 0.1 to 3 m thick	contains no local unconformities; has complete range of clast sizes (pebble to boulder)	gradational upper and lower	18 m	unimodal peak cluster	100's of m

Table 2.2. Detailed description of diamicton and associated lithofacies

Layered Diamicton (LD)	composed of > 70 % diamicton; attenuated to lenticular layers of diamicton and structureless sand and silt; layers are commonly horizontal, discontinuous, and are fault-bounded, or pinch-out laterally; layering thickness ranges from 0.1 to 80 cm	may contain recumbent folds; complete range of clast sizes up to boulders	sharp to gradational upper and lower	7.5 m	unimodal to broad polymodal	100's of m
Interbedded Sand Silt and/or Diamicton (IDSS)	20 to 70 percent diamicton; discontinuous bedding; sand and silt beds typically much thicker than in lithofacies SD; contains no dropstone-like structures	sorted sediment commonly exhibits primary bedding structures (horizontal and cross-bedding)		------		10's of m
(IDSS-T)	<u>Tabular bedded:</u> discontinuous, even, parallel bedded; sand beds range from 1 to 100 cm thick and silt and diamicton beds from 1 to 30 cm thick; absence of dropstone-like structures; no laterally persistent internal erosion surfaces	some diamicton beds contain an abundance of agglomerated diamicton balls; internal bedding planes between sand or silt and diamicton are wavy (loaded?); pebbles are rare		8.5 m		
(IDSS-L)	<u>Lenticular bedded:</u> chaotic interbedding of sand silt, gravel and diamicton; beds are lenticular; gravel and sand form small channel fills in underlying sand and silt beds; angular blocks of diamicton from pebble to large cobble size occur in places; beds range from 1 cm to 1 m thick	irregular clast- and matrix-supported pebble concentrations are common	sharp basal	12 m		10's of m
Intermittent Clast Concentrations (ICA)	discontinuous alignment of pebbles and cobbles along specific horizons at the base of, or within diamicton; clasts commonly partially enveloped by substrate; clasts are scratched, some with consistent orientations	no associated fine sediment; faceting of upper and/or lower clast surfaces common on softer lithologies		1 clast		100's of m
Undifferentiated (U)	predominantly diamicton but outcrop too poor to assign lithofacies					

Table 2.2 (continued)

C. Deformation Structures

A variety of postdepositional plastic and brittle deformation structures occur in Quaternary sediments in the study area (Table 2.1) and are classified according to scale. These structures may be found in more than one lithofacies or stratigraphic unit, or they may be restricted to contact zones between units. The genesis of these structures has a direct bearing on the interpretation of lithofacies and the stratigraphic sequence.

Large-scale deformation structures

Deformation structures are referred to as *large-scale* where they involve substantial parts of one or more lithofacies. Commonly, they affect greater than one metre of vertical section (e.g. Plates 1.1, 2.1 and 2.2).

Small-scale deformation

Deformation structures are referred to as *small-scale* where they affect only one lithofacies. Commonly they are smaller than 1 m. Folds that are preserved along fracture planes or zones resemble ridges and grooves when viewed at right angles to their axis (Plate 2.3). Normal faults show less than 5 cm of vertical offset. Fractures[2] are cracks that are restricted to horizons or zones within a lithofacies (Plates 2.4 and 2.5). In cliff faces, they commonly occur as linear features either straight and at an oblique angle or parallel to bedding planes or arcuate.

Fractures may contain small amounts of sorted sediment, commonly as scattered sand grains or as a film of silt. Attenuated structures are drawn-out remnants of pre-existing sediment contained within diamicton. Smears refer to small fragments of pre-existing sediment that have the appearance of having been smeared out, so that ends taper off into the diamicton host.

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[2]The term *jointing* is used to describe a network of cracks that are predominantly parallel and perpendicular to bedding, and along which no appreciable movement has occurred. A joint is defined as a surface of fracture or parting in a rock, without displacement; the surface is usually plane and often occurs with parallel joints to form part of a joint set (Bates and Jackson, 1980)

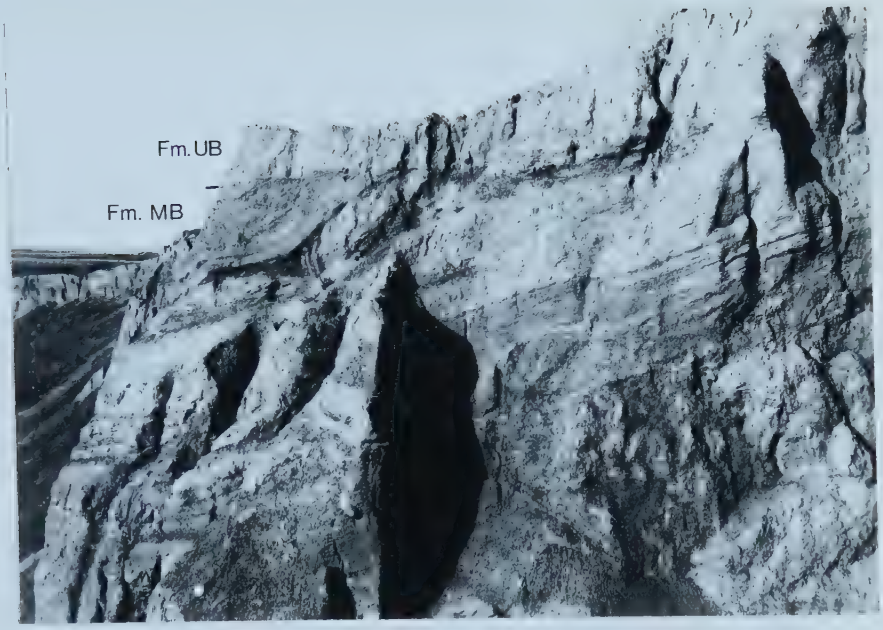


Plate 2.1. A large-scale recumbent fold structure in diamicton sand and silt in the central part of Golden Valley Bluff. The upper (UB) and middle (MB) members of formation B are shown in this 35 m high exposure.

Plate 2.2. A large-scale recumbent fold (centre of photograph) that includes the middle member of formation B at Golden Valley Bluff. The upper part of the exposure (above the arrow) shows silt of formation C. 'D' marks diamicton and 'D&S' marks diamicton (dark gray) that contains discontinuous silt beds (light gray).

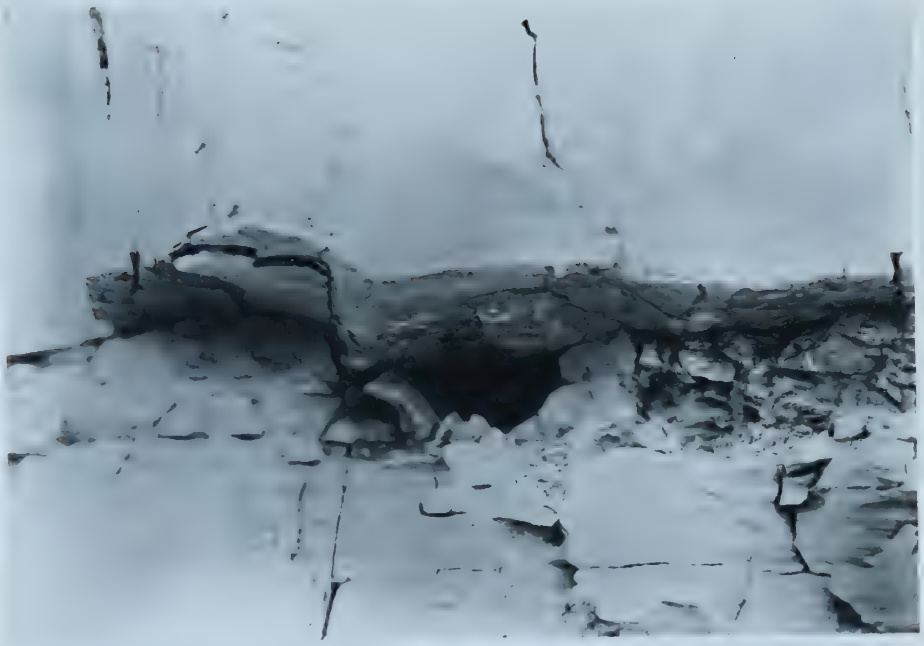


Plate 2.3. Small-scale asymetrical folds along the base of a diamicton where it overlies silt-clay rhythmites. The diamicton is at the base of formation A, and the silt-clay bed is part of the upper member of the Empress Formation. About 50 vertical m of section are shown.

Plate 2.4. A fracture plane within diamicton, bounded by sharp horizontal fractures, near DNP79-19 at the north end of Golden Valley Bluff. Note the arcuate shape of individual fractures within the fracture zone.

Plate 2.5. A 1.0 metre thick fracture zone along the basal contact of diamicton (formation A), where it overlies silt-clay rhythmites (upper member of the Empress Formation). The pick is 95 cm long.

Linear Structures

The orientation of linear structures can be represented by a trend and plunge. They include the following:

(1) Scratched and polished surfaces within the sediment (Plate 2.6). The scratches are straight and commonly occur in sets that have one or several preferred orientations.

(2) Scratches that occur in parallel sets on the surface of pebbles, cobbles, and boulders.

(3) The axes of glaciotectonic folds.

D. Guidelines to lithofacies classification

The following guidelines were used to develop a lithofacies classification for diamicton and associated sediment.

(1) Classification is based on the presence or absence of primary sedimentary characteristics that are diagnostic of a given lithofacies (e.g. stratification).

(2) Where a repetition or complex of simple lithofacies exists, a compound lithofacies term is used (e.g. if individual simple lithofacies are too thin or discontinuous to trace laterally).

The lithofacies names (Table 2.2) are designed to be succinct and descriptive and are intended to be used as an easy method of communicating the distinctive characteristics of each. Moreover, the detailed descriptions found in Table 2.2 and below provide an unambiguous characterization of each lithofacies. Two of the lithofacies (SD and IDSS) have been subdivided based on differences in their essential characteristics.

The diamicton in the study area has several general characteristics.

(1) It is matrix-supported with gravel concentrations of less than 10 percent by volume, averaging less than 5 percent.

(2) Its less-than-2-mm fraction ranges from 16 to 40 percent sand, 34 to 42 percent silt and 28 to 43 percent clay (Fig. 2.1).

(3) Stratification and layering are the most evident structures present in association with this lithotype and are used as one of the primary means of differentiating lithofacies.

The terms *stratified*, *layered*, and *unlayered* are used extensively in lithofacies

Plate 2.6. A polished and scratched fracture plane within diamicton at the base of formation A. About 16 cm of a pick head are shown in this photograph.

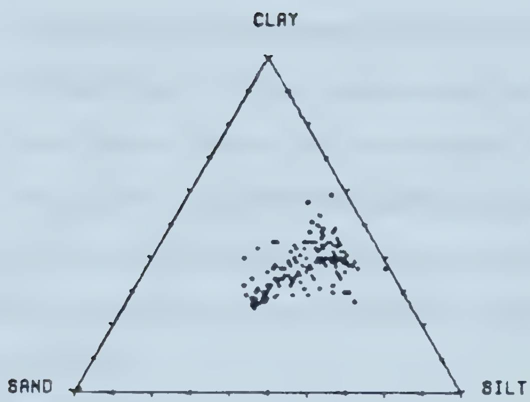


Figure 2.1. Ternary diagram showing the sand-silt-clay content of all diamicton samples analyzed in the study.

descriptions. The obvious problem with this terminology involves the question of whether a diamicton-lithofacies is stratified, layered or simply a sequence of interbedded diamicton and non-diamicton lithofacies.

Where a diamicton has a more or less homogeneous-looking internal structure, it is referred to as *unlayered*. Regular joints that define blocky, prismatic and columnar diamicton outcrop surfaces are not considered in this classification because they are not depositional structures.

A diamicton lithofacies is referred to as *stratified* where multiple bedding or lamination planes of well-sorted sediment occur throughout it and form less than 20 percent of the volume of the lithofacies. Component diamicton beds within the stratified lithofacies are generally much less than 1 m thick, whereas well-sorted sediment beds are commonly less than 1 cm thick. None of these beds can be easily traced horizontally for more than about 20 m. In many places, unlayered diamicton composes some or all of the diamicton component of stratified diamicton lithofacies. However, for simplicity, it is included within the stratified lithofacies, because stratification is the predominant characteristic of the entire lithofacies.

Where sorted sediment is 20 to 90 percent of a stratified sequence, the term *interbedded* is used along with the components present: e.g.; interbedded sand and diamicton. Other primary structures present within a given diamicton unit are described in its characteristics. In particular, lenses, beds, and unlithified inclusions are described with emphasis placed on degree of sorting, presence of intraclasts, internal bedding or banding, types of folding, faulting, lens geometry, and, nature of contacts with surrounding diamicton.

The term *layered* refers to a structure that is formed by differences in diamicton lithology or sediment type within a diamicton lithofacies. Layers range from about one mm to about 80 cm thick and can be traced laterally for up to 15 m. Where lateral termination of individual layers has been observed, they taper gradually and ultimately pinch out. Layering is a nongenetic term whereas stratification refers to sedimentary bedding or lamination). The term *diamicton containing lenses (DCL)* is used to describe diamicton that contains 10 to 30 percent sand and silt lenses.

Where outcrop exposure and accessibility are too poor to allow detailed examination, the term *undifferentiated* is used.

Fabric

The preferred orientation of microclasts is presented on rose diagrams as one of the characteristics of diamicton within lithofacies. It is two-dimensional and is described in terms of the nature of the distribution, that is, whether it is unimodal (distribution around one preferred orientation), bimodal, or polymodal. In addition, the width of a given trend or peak on the rose diagram (narrow or broad) gives a measure of its relative strength. In many cases, reference is made to a 'cluster' of peaks, where several peaks are close together and define a broad direction of preferred orientation. The narrower the scatter about a given trend, the stronger is the preferred orientation. These orientation data are presented in 360° mirror image form on rose diagrams because the direction of the trend is not known.

E. Lithofacies

The location of measured sections referred to in the following descriptions are shown on Figure 2.2 and are described in Appendix A.

Unlayered Diamicton (UD)

Unlayered diamicton is used to describe diamicton that has a more or less homogeneous internal structure (Plate 2.7). It commonly ocurs in beds ranging from 1 to 7 m in thickness, and contains a range of clast sizes from small pebbles to large boulders (up to 2 m in diameter). In a few places this lithofacies contains inclusions of unlithified sediment, generally as undeformed lenses which appear to be in their primary depositional orientation (Plate 2.8). Small attenuated bands (smaller than 1 cm by 5 cm) of clay and silt were observed in the basal 10 cm of unlayered diamicton at some localities (DNP79-17 and DNP81-8; Fig. 2.2). Beds of unlayered diamicton can be traced laterally for hundreds of metres. Their basal contacts are commonly sharp (Plate 2.9), whereas their upper contacts are gradational (Plate 2.10). Microclast orientations in unlayered diamicton range from polymodal with one broad trend (Fig. 2.3: a , b and c) to polymodal with no preferred

Figure 2.2. Location of measured sections and testholes.

Golden Valley Bluff South DNP82 100
Golden Valley Bluff South Medicine Hat Dump Section DNP82 8A
Golden Valley Medicine Hat Dump Section DNP82 8B
Golden Valley Medicine Hat Dump Section DNP82 8C
Golden Valley Bluff Centre DNP78 13
Golden Valley Bluff South DNP81 6
Golden Valley North DNP78 14
Golden Valley North DNP79 16
Golden Valley North DNP79 19
Golden Valley North DNP81 8 (Lehr Gully area)
Golden Valley North DNP79 17 and DNP80 52
Golden Valley North DNP81 10
Evilsmelling Bluff Centre DNP79 11
Evilsmelling Bluff Centre DNP79 14
Island Bluff West DNP78 5
Island Bluff West DNP81 15

A	GSC 69-4
B	GSC 69-2
C	GSC 69-1
D	GSC 69-3
E	GSC 73TC
F	GSC 69-5
G	GSC 73GV
H	GSC 69-7
I	GSC 69-6
J	GSC 73RC

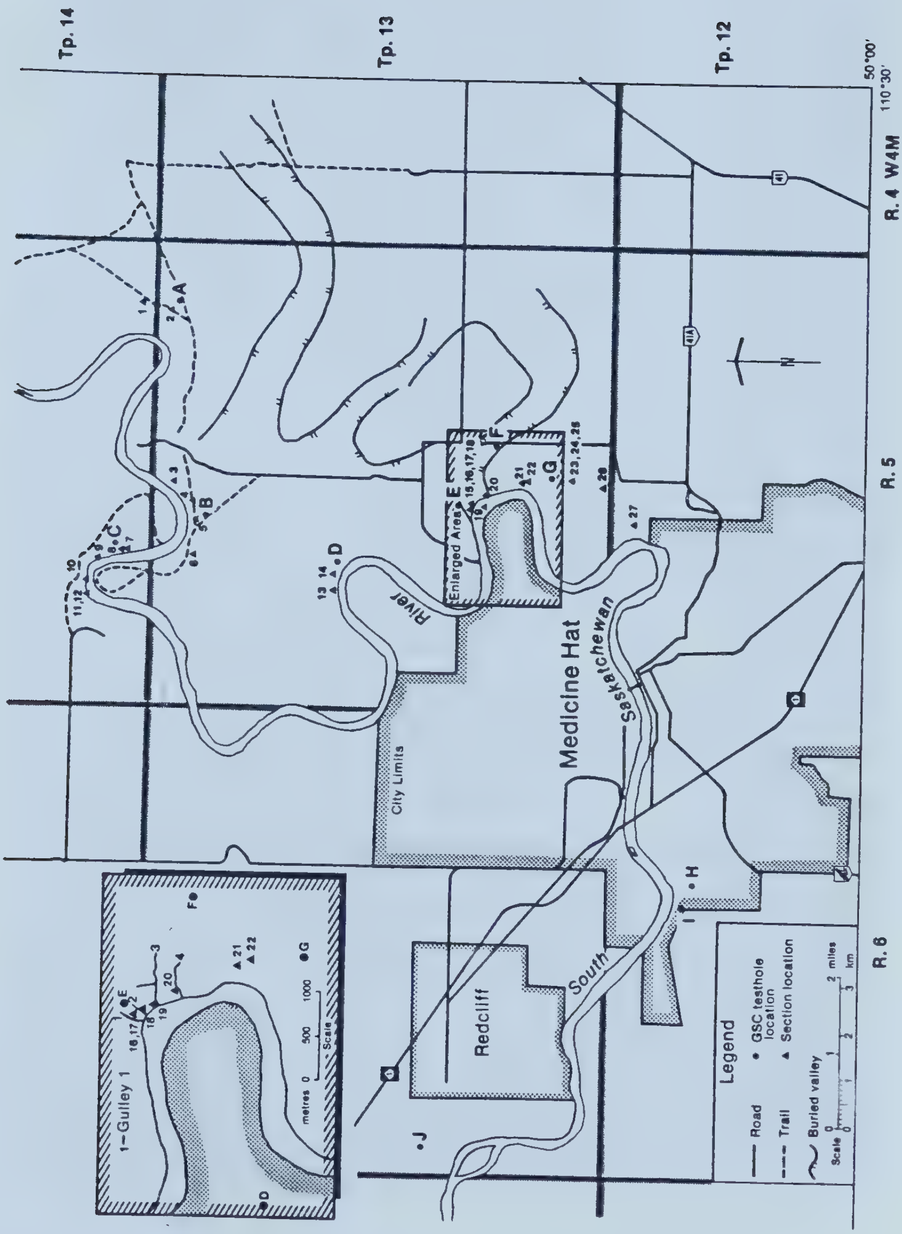
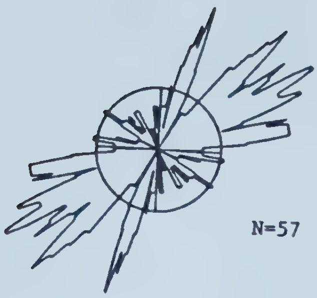

Tp. 14
Tp. 13
Tp. 12
R. 4 W4M
R. 5
R. 6
50°00'
110°30'
Medicine Hat
Redcliff
South
Saskatchewan
River
City Limits
Enlarged Area
1–Gulley 1
metres 0 500 1000
Scale
Legend
Road
Trail
Buried valley
GSC testhole location
Section location
Scale
miles
km

Plate 2.7. Unlayered diamicton (UD) has no visible structure.

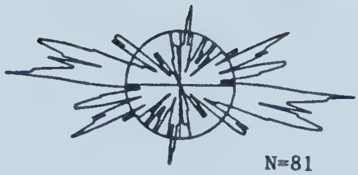
Plate 2.8. Small undeformed sandy gravel lenses in unlayered diamicton (UD) near the base of the upper member of formation B.

Plate 2.9. Sharp basal contact of unlayered diamicton (lithofacies UD), along the central part of Golden Valley Bluff. Formation A (Fm. A), the middle (Fm. MB) and upper (Fm. UB) members of formation B are shown in this 50 m high exposure.

Plate 2.10. Gradational upper contact of unlayered diamicton (lithofacies UD) with lithofacies DCL (diamicton containing lenses) at Evilsmelling Bluff. About 9 vertical m of section are shown.

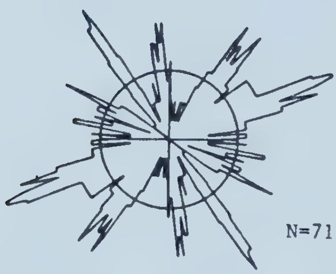


a. DNP78-4, unit 2



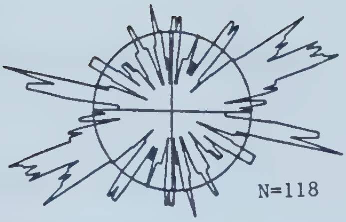
b. DNP78-4, unit 1

c. DNP81-8, unit 2

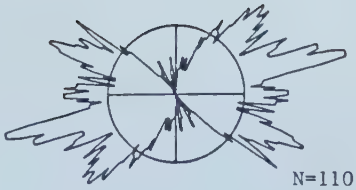


d. DNP78-4, unit 2

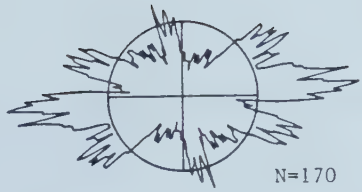
Figure 2.3. Rose diagrams (10 degree moving average) showing the variation in microclast orientation for samples of lithofacies UD (unlayered diamicton).



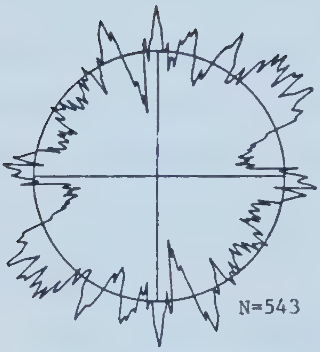
e. DNP78-4, unit 12



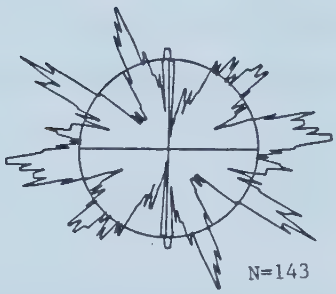
f. DNP78-4A, unit 12



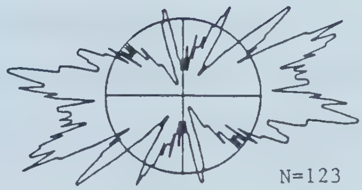
g. DNP81-6, unit 7



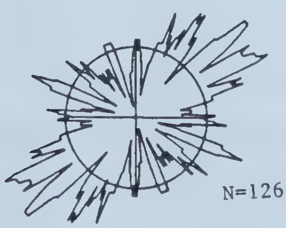
h. DNP79-11, base of unit 9



i. DNP78-13, base of unit 7



j. DNP78-8, unit 5



k. DNP81-15, unit 2

Figure 2.3. (continued)

orientation (Fig. 2.3: d and h). Other lithofacies may contain unlayered diamicton as a component, but individual beds are generally less than 1 m thick and occur as part of a thicker coherent bed.

Stratified Diamicton (SD)

Lithofacies SD is comprised of parallel, interstratified, undeformed sand, silt, and diamicton (Plate 2.11 and 2.12) of which about 80 to 98 percent is diamicton. Diamicton beds range from 1 to 100 cm thick, whereas sand and silt beds range from 0.1 to 10 mm thick. It is important to note that lithofacies SD does not contain sand or silt lenses and generally has a smaller proportion of large pebbles and cobbles than other diamicton lithofacies. Bedding planes are commonly parallel and horizontal, but are difficult to trace over lateral distances of more than 10 to 20 m because of outcrop accessibility problems. Primary structures such as cross-bedding, horizontal bedding, and lamination occur within thicker (1 cm) well sorted sediment beds. Internal contacts between well-sorted sediment and diamicton, and at the base of this lithofacies are sharp; however, the upper lithofacies contact varies from sharp to gradational. Lithofacies SD ranges up to 7 m in thickness.

The two-dimensional orientation of microclasts within the diamicton of this lithofacies (SD) ranges from a polymodal distribution that has no dominant peaks (Fig. 2.4: a, b, d, f) to bimodal (Fig. 2.4: e), with two peaks in the same quadrant and some background scatter.

The relationship between stratification and pebble- and cobble-sized clasts in this lithofacies is illustrated on Figure 2.5. Clast 1 in this diagram truncates the laminae (e.g. Plate 2.13). Stratification conforms to the upper and lower surfaces of clast 2 (Plate 2.14). Laminae above and/or below a clast conform in this manner only if they are within approximately one clast diameter of its upper or lower surface. Clast 3 is contained within a single diamicton bed and has no deformation of stratification above or below it. Elongate or flattened clasts within lithofacies SD commonly lie horizontally.

Rounded soft sediment clasts (intraclasts) occur in small quantities within the lithofacies. Striated clasts have been observed in lithofacies SD. However, it seems to contain a larger proportion of angular clasts than other diamicton lithofacies. No local

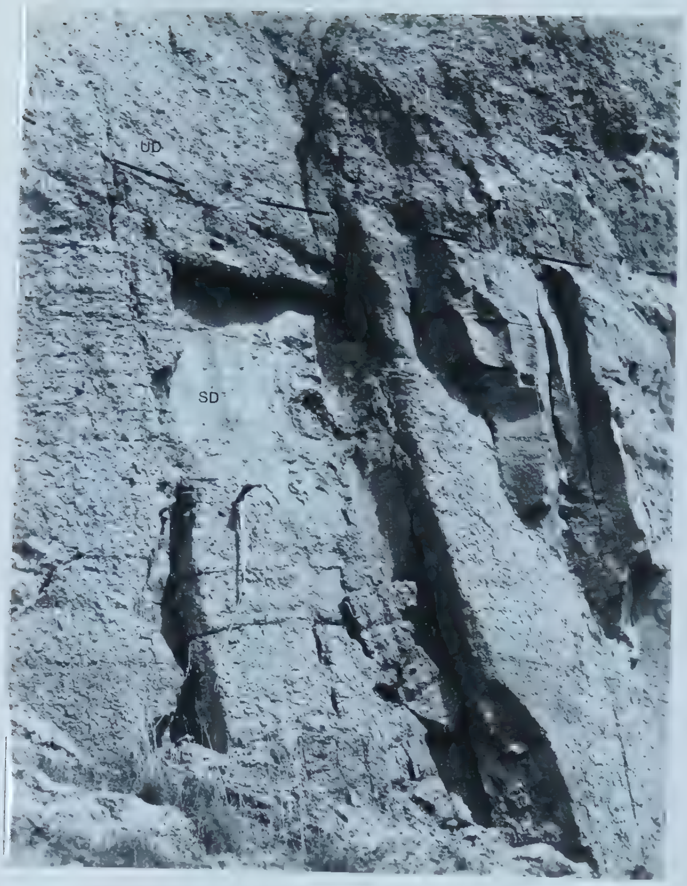
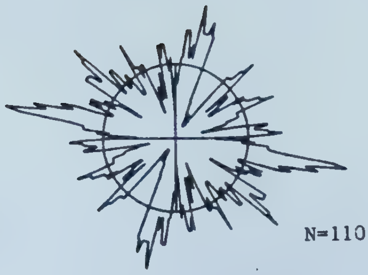
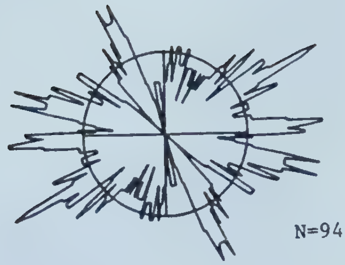


Plate 2.11. Stratified diamicton (lithofacies SD-L) that has lamination. Lithofacies SD is gradationally overlain by unlayered diamicton (lithofacies UD). Photo taken at DNP79-11, Evilsmelling Bluff. The pick is 95 cm long.

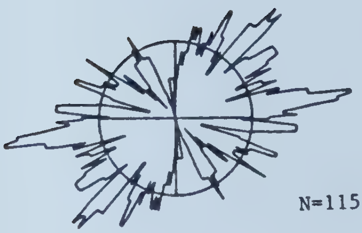
Plate 2.12. Stratified diamicton (lithofacies SD); the thin horizontal beds are silty sand 0.2 to 1.5 cm thick. The vertical lineations are due to silt slope wash. Photo taken near DNP79-14 at Evilsmelling Bluff. The knife is about 13 cm long.



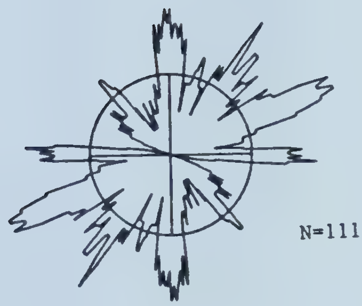
a. DNP79-11, unit 7, #4



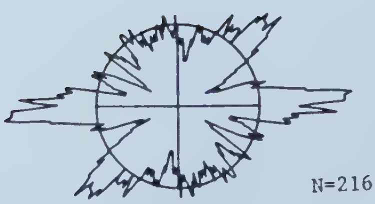
b. DNP79-11, unit 7, #3



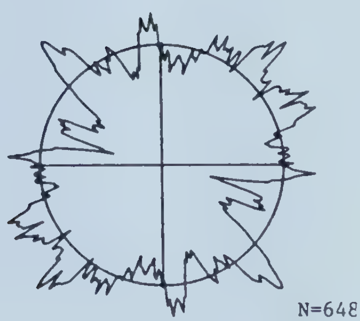
c. DNP79-11, unit 7, #2



d. DNP79-11, unit 7, #1



e. DNP79-14, unit 3



f. DNP79-11, unit 7

Figure 2.4. Rose diagrams (10 degree moving average) showing the variation in microclast orientation for samples of lithofacies SD (stratified diamicton).

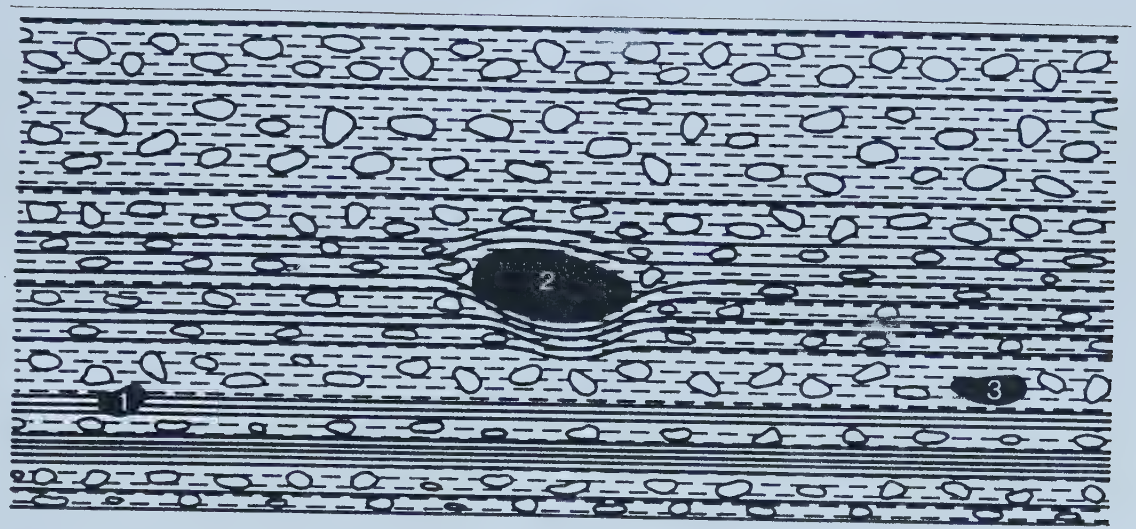


Figure 2.5. Schematic diagram of lithofacies SD (stratified diamicton) showing the relationship of clasts to stratification.

Plate 2.13. Close-up of lithofacies SD-L showing lamination within diamicton. Note that the pebble above the finger cuts the lamination.

Plate 2.14. Close-up of lithofacies SD-B.
Note that stratification conforms to the upper and lower surfaces of the boulder.

incised erosional surfaces have been observed within lithofacies SD. Lithofacies SD has one subfacies -- *laminated* stratified diamicton (Table 2.2).

Stratified Diamicton -- Laminated (SD-L)

Sublithofacies SD-L consists of 1 to 20 cm thick internally laminated diamiction beds interbedded with 0.1 to 10 mm thick, undeformed, subparallel sand and silt beds (Plates 2.11 and 2.12). The faint lamination in component diamicton beds with internal gradational contacts is due to grain size differences between laminae (Plate 2.13). In most places, the upper and lower contacts of diamicton and sand, silty sand, and silt beds are sharp with irregularities averaging 1 to 3 cm in relief. Normal grading in silty sand beds was observed in a few places. Rounded clasts of unconsolidated clay are rare, but occur throughout the diamicton. In a few places, diamicton beds contain thin, discontinuous, deformed silt and sand laminae. Sublithofacies SD-L is up to 4 m thick.

The lower contact of sublithofacies SD-L is conformable with the underlying surface and is typically sharp, whereas the upper contact is gradational. The photomicrograph shown on Plate 2.15 is a vertically oriented section through a portion of lithofacies SD-L at DNP79-11 (Plate 2.16). One horizontal, silty, fine sand lamination approximately 1 mm thick can be seen in the upper part of the photomicrograph. At this scale the upper and lower contacts are irregular. No primary structures have been observed within the laminations.

Two-dimensional microfabric data from four different diamicton beds within the one metre interval shown in Plate 2.16 exhibit polymodal orientations with abundant scatter (Figure 2.4: a-d). Another sample from lithofacies SD shows similar scatter (Fig. 2.4: f).

Diamicton containing lenses (DCL)

The lithofacies referred to as diamicton containing lenses contains 10 to 30 percent sand and silt lenses (Plate 2.17) in a predominantly diamicton (70 to 90 percent) deposit. Sand and silt lenses (Plate 2.17) range from about 5 cm thick by 2 m long to 2 by 3 m, are irregular in shape and may contain pebbles. Clasts within lithofacies DCL range up to medium cobble size. Two types of internal deformation occur in lenses within

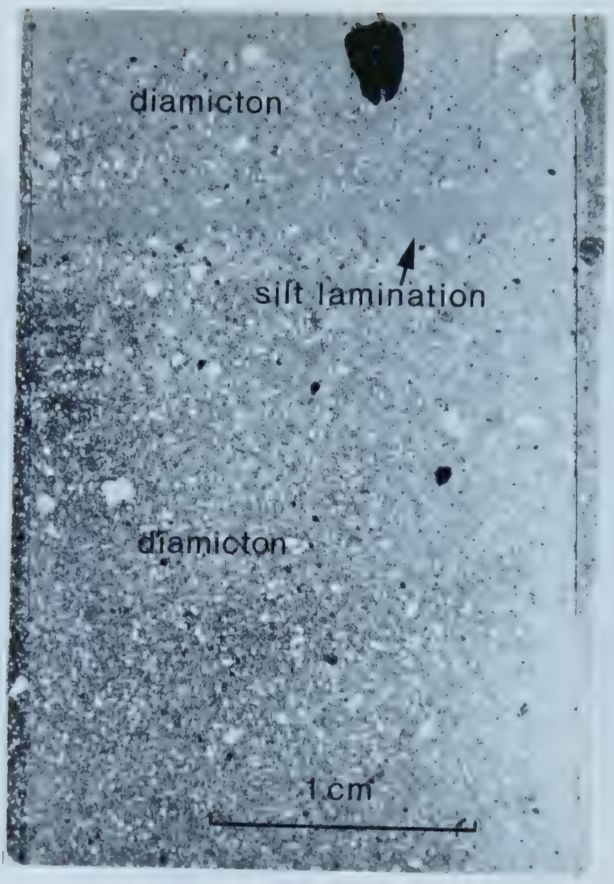


Plate 2.15. Vertically oriented photomicrograph through part of lithofacies SD-L.

Plate 2.16. Location of four oriented samples taken from an outcrop of lithofacies SD-L (arrows).

Plate 2.17. Deformed sand lens within lithofacies DCL (diamicton containing lenses, upper member of formation B) at Evilsmelling Bluff. Deformation probably resulted from collapse. Exposure is 10.5 m high.

lithofacies DCL:

1. Normal faulting with offsets ranging from one millimetre to tens of centimetres, and
2. Synformal folds that are probably collapse structures.

Upper and lower contacts of lithofacies DCL are gradational. This lithofacies is up to 6 m thick, extends for hundreds of metres and contains no local unconformities.

Deformed stratified diamicton (DSD)

Lithofacies DSD is predominantly composed of diamicton (greater than 85 percent). It has discontinuous deformed beds of silty clay diamicton, sandy silt diamicton, and sand and silt (Plate 2.18) and contains a complete range of clast sizes from pebbles to boulders. Deformation is similar to soft-sediment deformation structures (injection or load). Microfabric data from samples of lithofacies DSD show (i) polymodal distributions with a single strong peak (Fig. 2.6, a) (ii) polymodal distributions with several strong peaks (Fig. 2.6: b and d) and (iii) wide scatter in preferred orientation about a single direction (Fig. 2.6: c). Lithofacies DSD extends for hundreds of metres, is up to 18 m thick, and contains no local unconformities.

Layered Diamicton (LD)

Lithofacies LD is characterized by attenuated to lenticular, horizontal layers of diamicton and structureless sand and silt (Plate 2.19). It contains more than 70 percent diamicton and layers are thin (0.1 to 80 cm) relative to their horizontal dimension, commonly discontinuous, and cannot be traced for more than 10 to 15 m. Many layers are fault-bounded or laterally attenuated along fracture planes. A microfault in lithofacies LD with some lateral displacement is shown on Plate 2.20. Diamicton that does not contain identifiable stratification but has horizontal, subparallel partings has been included in lithofacies LD (DNP78-13, unit 6). Recumbent folds and horizontal and oblique fractures that extend for more than 3 m into the sediment are common in LD sediment. Lithofacies LD contains a complete range of clast sizes from grit to boulders, ranges from 3.7 to 7.5 m in thickness, and has a sharp basal contact.

Two-dimensional microfabric data from lithofacies LD exhibit a wide range of distributions including (i) unimodal, (Fig. 2.7: j), (ii) bimodal, with narrow peaks relatively

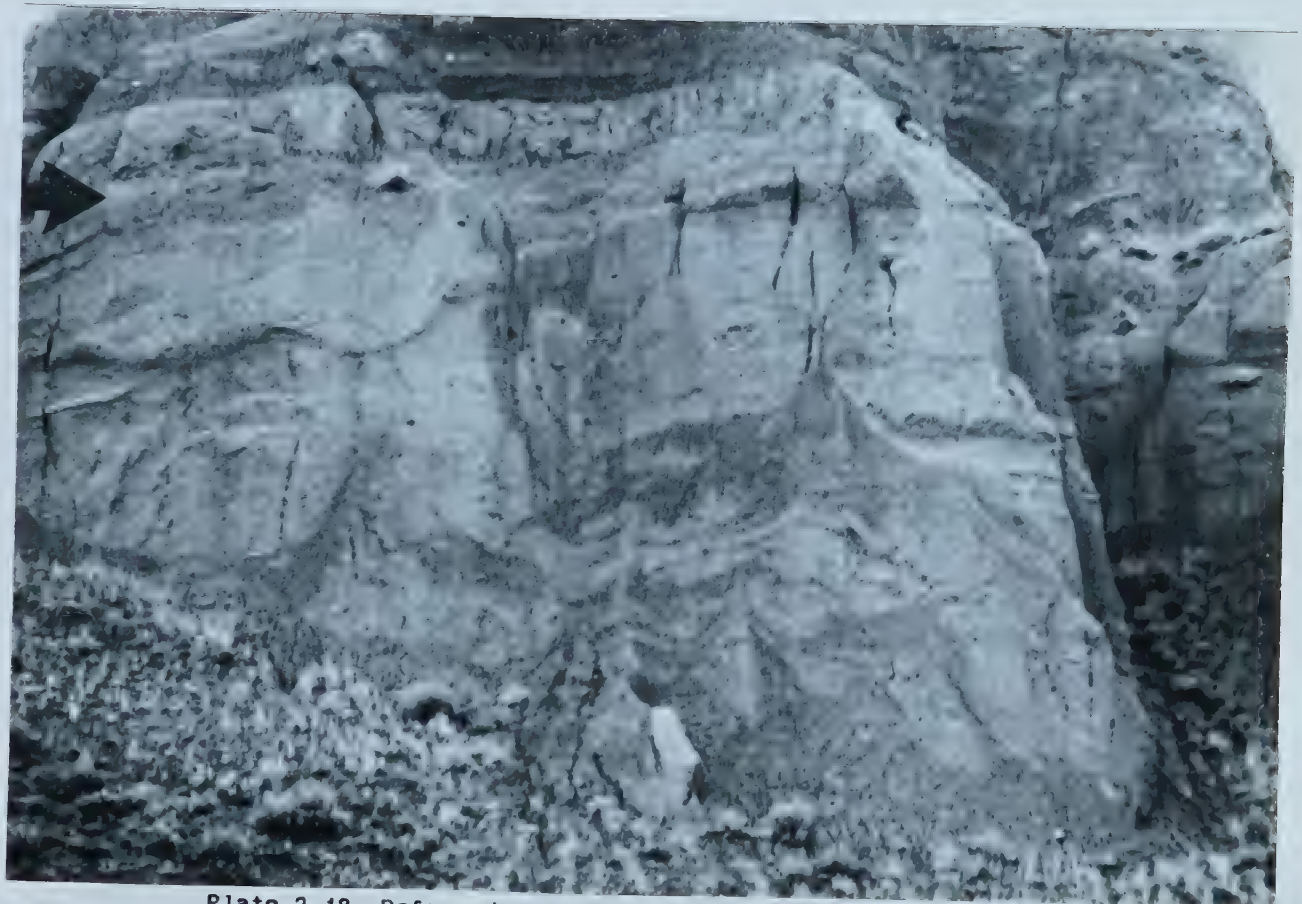
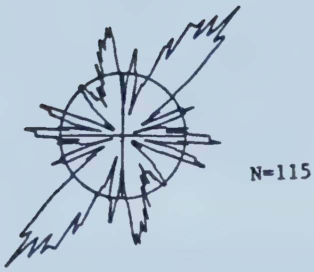
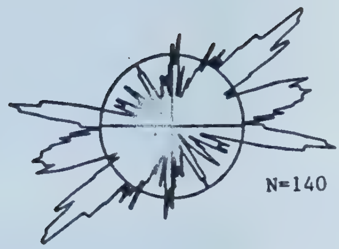


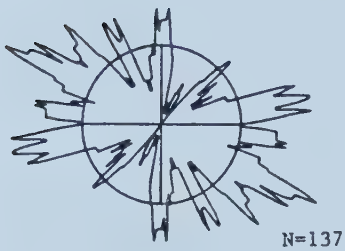
Plate 2.18. Deformed stratified diamicton (DSD) has deformation structures that could be due to injection or collapse. The upper contact of lithofacies DSD is marked by the arrow. Above the arrow is a 2.5 m exposure of lithofacies IDSS-T. About 22 m of outcrop are shown (formation A, central part of Golden Valley Bluff).



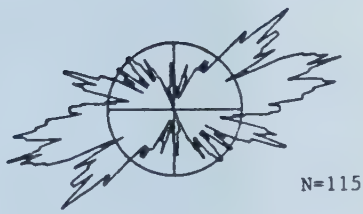
a. DNP81-6, unit 1 (-17.2m)



b. DNP81-6, unit 1 (-19.8m)



c. DNP81-6, unit 1 (-19.9m)



d. DNP81-6, unit 1 (-26.6m)

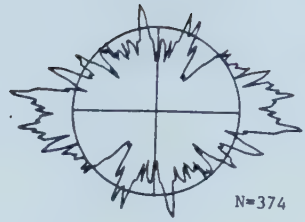
Figure 2.6. Rose diagrams (10 degree moving average) showing the variation in microclast orientation for samples of lithofacies DSD (deformed stratified diamicton).

Plate 2.19. Close-up of layered diamicton (lithofacies LD). Refer to Plate 3.10 for a smaller scale photograph of LD. The prismatic jointing is interpreted to be the result of stress release towards the valley wall.

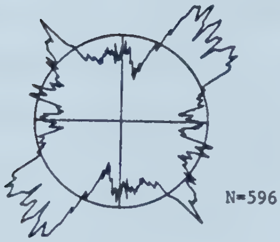
Plate 2.20. Photomicrograph of lithofacies LD diamicton showing a probable microfault (arrow).

a. DNP81-14, top of unit 4

b. DNP81-14, base of unit 4

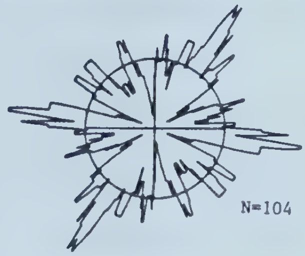


c. DNP79-11, unit 4

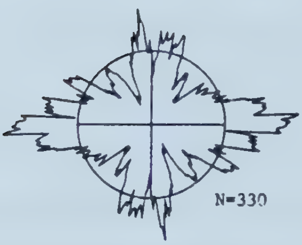


d. DNP79-11, unit 6

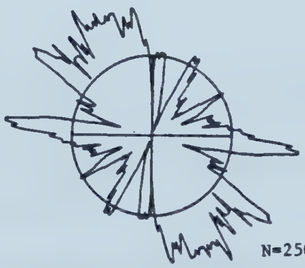
e. DNP79-11, unit 6 (-31.2m)



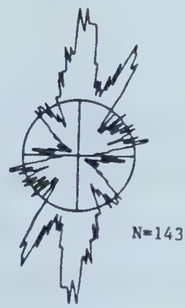
f. DNP78-13, unit 6



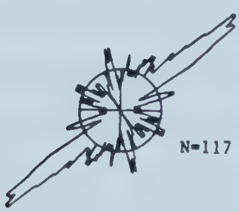
g. DNP78-13, unit 6



h. DNP79-14, unit 2



i. DNP79-14, unit 2



j. DNP78-4, unit 5

Figure 2.7. Rose diagrams (10 degree moving average) showing the variation in microclast orientation for samples of lithofacies LD (layered diamicton).

close together (Fig. 2.7: i), (iii) bimodal, with broad peaks at about right angles (Fig. 2.7: d and e), and (iv) broad polymodal, with up to ±60 degrees of scatter (Fig. 2.7: a).

Lithofacies LD has only been observed in the middle member of formation B. It is best exposed at Evilsmelling Bluff (DNP79-14, unit 2, Plate 2.19).

Interbedded Diamicton, Sand, and Silt (IDSS)

Lithofacies IDSS is composed of diamicton and sand or silt, with diamicton forming 20 to 70 percent of the total volume. Beds are commonly discontinuous within this lithofacies, so that mapping of individual beds is not practical. This lithofacies differs from stratified diamicton (SD) in the following characteristics: (i) IDSS contains considerably less diamicton, (ii) IDSS bedding is typically much thicker than in lithofacies SD, especially sand and silt beds, and (iii) no dropstone features were observed (pebbles or cobbles with associated deformation of sediment beneath and draping over them). Two subdivisions of lithofacies IDSS have been made on the basis of bedding geometry and consistency.

Tabular Bedded (IDSS-T)

The distribution and relationship of beds and laminae varies greatly at most exposures of lithofacies IDSS-T; however, bedding is dominantly tabular. In some places sand beds predominate, with thicknesses of up to 1 metre whereas diamicton and silt beds range from 1 to 30 cm thick (Plate 1.2). Elsewhere, these lithotypes occur in different proportions (Fig. 2.8). Sand beds are generally cross and horizontally bedded, forming sheet-like deposits rather than having a channel geometry. Silt beds are commonly massive or laminated with similar geometry to the sands. Where diamicton beds are interbedded with horizontal bedded sand, some of the diamicton beds contain an abundance of agglomerated diamicton balls. Elsewhere, the diamicton is unlayered or convoluted with or without silt and clay intraclasts. In these places, wavy internal contacts between diamicton and sand, or silt probably indicate that loading along these contacts has occurred. Pebbles are rare, but occur in all bedding lithotypes and fine gravel lenses or beds are found in a few places. The lower and upper contacts of lithofacies IDSS-T are gradational. Upwards gradation to rhythmically bedded silt and clay was observed in some places.

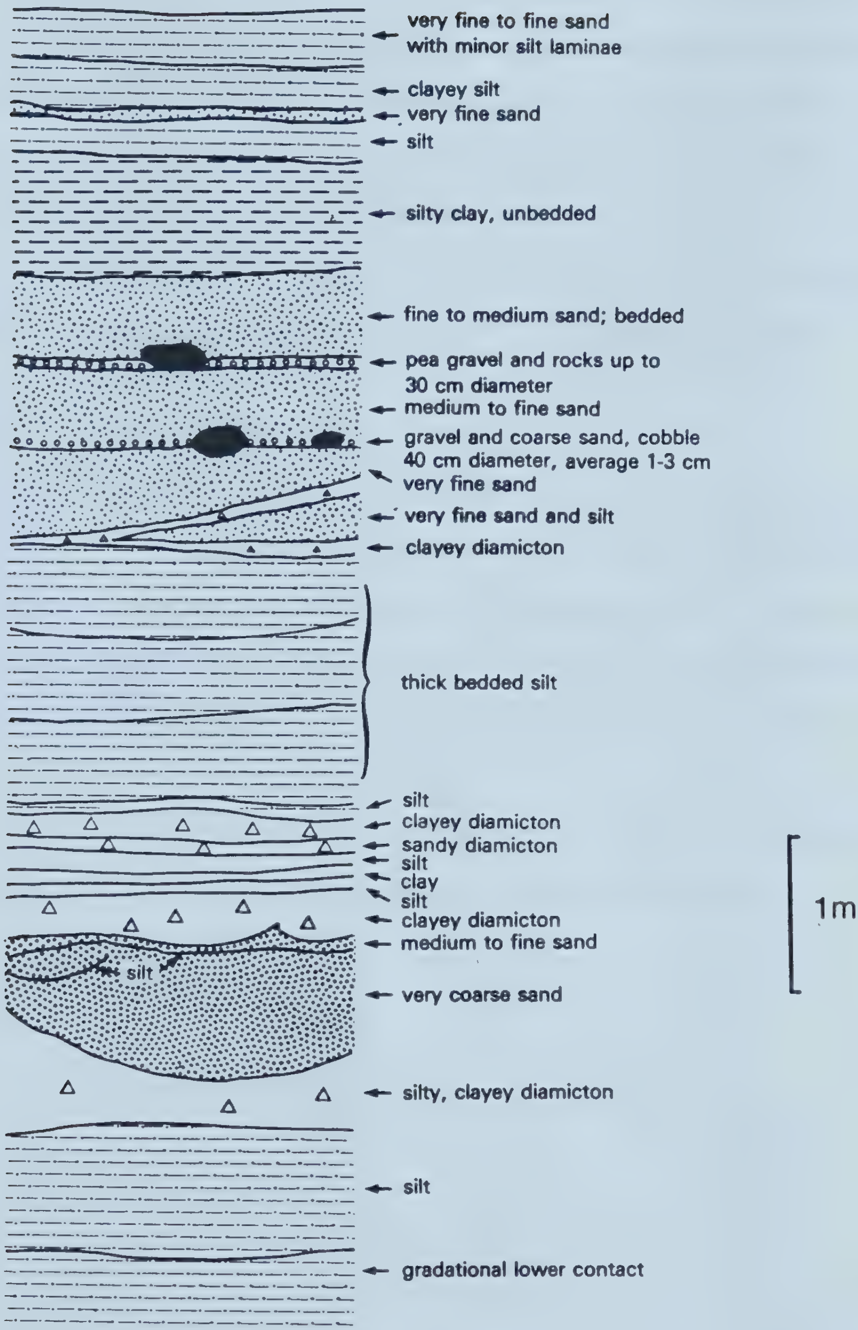


Figure 2.8. Sketch of lithofacies IDSS-T (interbedded diamicton, sand, and silt - tabular bedded) at Mitchell Bluff (DNP78-8).

Lithofacies IDSS-T deposits are up to 8.5 m in thickness.

Interbedded Diamicton, Sand, Silt and Gravel -- Lenticular (IDSS-L)

Lithofacies IDSS-L has similar lithotype components to facies IDSS-T, but bedding is mainly lenticular and much more irregular and discontinuous with small cut-and-fill structures infilled with sand and gravel throughout (Plates 2.21 and 2.22). Pebble concentrations and rounded (Plate 2.21) and angular clasts (Plate 2.22), up to 1 by 2 m in size, of pre-existing unlithified sediment occur in some places. Bed thicknesses are highly variable, ranging from about 1 cm to 1 m, but can be traced laterally for up to tens of metres. Lithofacies IDSS-L deposits are up to 12 m thick.

Intermittent Clast Alignments (ICA)

Intermittent clast alignments are thin, discontinuous, generally horizontal, one clast thick layers of pebble- to boulder-sized clasts that are commonly partially enveloped by the upper portion of an underlying sediment unit. The clasts are so far apart that their presence at a specific horizon is best seen from a distance. Flat clasts generally lie parallel to the contact on which they occur. Many component carbonate clasts are scratched and polished with faceting on some upper and lower surfaces. In places, upper surface clast scratches show broad but consistent orientations. No sediment finer than pebbles has been recognized in association with these intermittent clast alignments.

Plate 2.21. Lithofacies IDSS-L (lenticular bedded, interbedded diamicton, sand, and silt) is composed of interbedded diamicton, sand, silt and gravel (north end of Golden Valley Bluff).

Plate 2.22. A large angular stratified intraclast within lithofacies IDSS-L (lenticular bedded, interbedded diamicton, sand, and silt) in formation C at the north end of Golden Valley Bluff.

III. LITHOSTRATIGRAPHY

A. Introduction

The following Quaternary lithostratigraphic framework has been constructed for the Medicine Hat area as a result of this study. It is based primarily on outcrop data and is augmented with subsurface testhole data. The most complete sequence is exposed at Golden Valley Bluff (Figure 1.2) where all four formations (Table 3.1) are exposed. Correlation between outcrops is based on field relationships, including lithofacies sequences, the stratigraphic position of major unconformities, and on the physical properties of units. Organic material adequate for radiocarbon dating or fauna for relative dating was not found during this study. A summary cross section of the lithostratigraphy is presented on Figure 3.1 (in pocket) and located on Figure 3.2. Outcrop names used in the text are shown on Figure 1.2.

The oldest Quaternary sedimentary sequence in the area is referred to as the *Empress Formation*, following the nomenclature of Whittaker and Christiansen (1972), who defined the Empress Group to include all unlithified sediment between the pre-Pleistocene surface and the lowest till in the stratigraphic sequence. The stratigraphic rank is decreased to formation in this report because the subunits within this formation cannot be mapped in this area.

The Empress Formation is divided into three members in the study area. The *lower member* consists of sand, sandy gravel, and gravel that is devoid of crystalline material derived from the Canadian Shield and it occurs at the base of the unlithified sequence in valley-fill that overlies Cretaceous rock.

The *middle member* is dark gray interbedded silt and clay that sharply overlies the lower member and grades upwards into cross-bedded sand. Material derived from the Canadian Shield is absent.

The *upper member* consists of a sequence of weakly laminated silt and sand capped by rhythmically bedded silt and clay that grades upwards from the middle member. It contains a few pebbles derived from the Canadian Shield.

The units of the Quaternary sequence that overlie the Empress Formation have been informally named to avoid confusion because this lithostratigraphic interpretation

Formation	Member	Lithology	Characteristics	Nature of contacts	Maximum thick-ness	Lithofacies present	Geographic distribution	Quality; extent of exposure
C	------	silt, clay, sand, dia-icton and gravel	includes all sediment that overlies or was deposited after formation B; surface loca-tions include material				isolated surface occurrences	good; limited
			(i) in depressions on top of formation B,	gradational	3 m	silt-clay interbeds cross-bedded sand		
			(ii) as cliff-top sediments,	sharp basal	3 m	very fine sand and silt		
			(iii) as gully fill, and	sharp basal	8 m	IDSS-L		
			(iv) on the modern alluvial plain	---------		sand, gravel and silt		
B	upper	diamicton	light yellowish brown (2.5Y 6/4 dry); silty sand matrix; columnar jointed (1 x 2 m x thickness of unit); contains rocks up to large cobble-size, including material derived from the Canadian Shield	sharp to gradational basal	8 m (out-crop) 23 m (holes)	DCL UD ICA	widespread	good; extensive
	middle	silty sand	fines upwards from thickly bedded silty sand to weakly laminated sandy silt	gradational basal		thick bedded silty sand; weakly lamin-ated sandy silt	widespread	good; limited
		diamicton, sand and silt	dark grayish brown (2.5Y 4/2 dry) with a dark red (2.5YR 3/6 dry) joint face stain; clayey silt to silty clay matrix; well developed blocky structure (1-4 cu. cm) distinctive banding and stratification; commonly has large-scale deformation; contains Canadian Shield material	sharp basal		SD LD IDSS-T	widespread	good; extensive
	lower	sand and gravel	grades upwards from a sandy gravel lag 10 to 70 cm thick, to horizontal and cross-bedded sand	sharp basal	> 8 m	cross-bedded sand, gravel	discon-tinuous	good; limited

Table 3.1. Detailed description of Quaternary lithostratigraphic units

A	------	diamicton	grayish brown (2.5Y 6/4 dry) to very dark grayish brown (2.5Y 3/2 dry); clayey silt matrix; contains Canadian Shield stones as large as cobbles; abundant large sandstone inclusions occur in some places	sharp basal	> 27 m	IDSS-T PSD MD	not present west of Golden Valley Bluff	good; limited
Empress	upper	silt and clay	fines upwards from weakly laminated silt to silt-clay rhythmites in upper 1 m; load structures in basal part of member; contains some Canadian Shield material	gradational basal contact	< 6 m	laminated silt and clay laminated silt	widespread	good; limited
	middle	medium to fine sand	cross-bedded with some climbing ripple beds; scours are up to 1 m deep and commonly are infilled with silt and clay intraclasts; contains no Canadian Shield derived material	gradational basal	12 m	cross-bedded sand	widespread	good; limited
	middle	very fine sand; silt and clayey silt	dark gray (2.5Y 7/2 dry); even, parallel bedded; beds are laminated and are 5 to 30 cm thick	sharp basal	5 m	interbedded very fine sand, silt and clayey silt	widespread	fair; limited
	lower	sand and gravel	quartzitic clast supported (?) pebbly to cobbly; no Canadian Shield material; directly overlies pre-Pleistocene material	sharp basal	8 m	--------	widespread (in test-holes only)	N/A; none

Table 3.1 (continued)

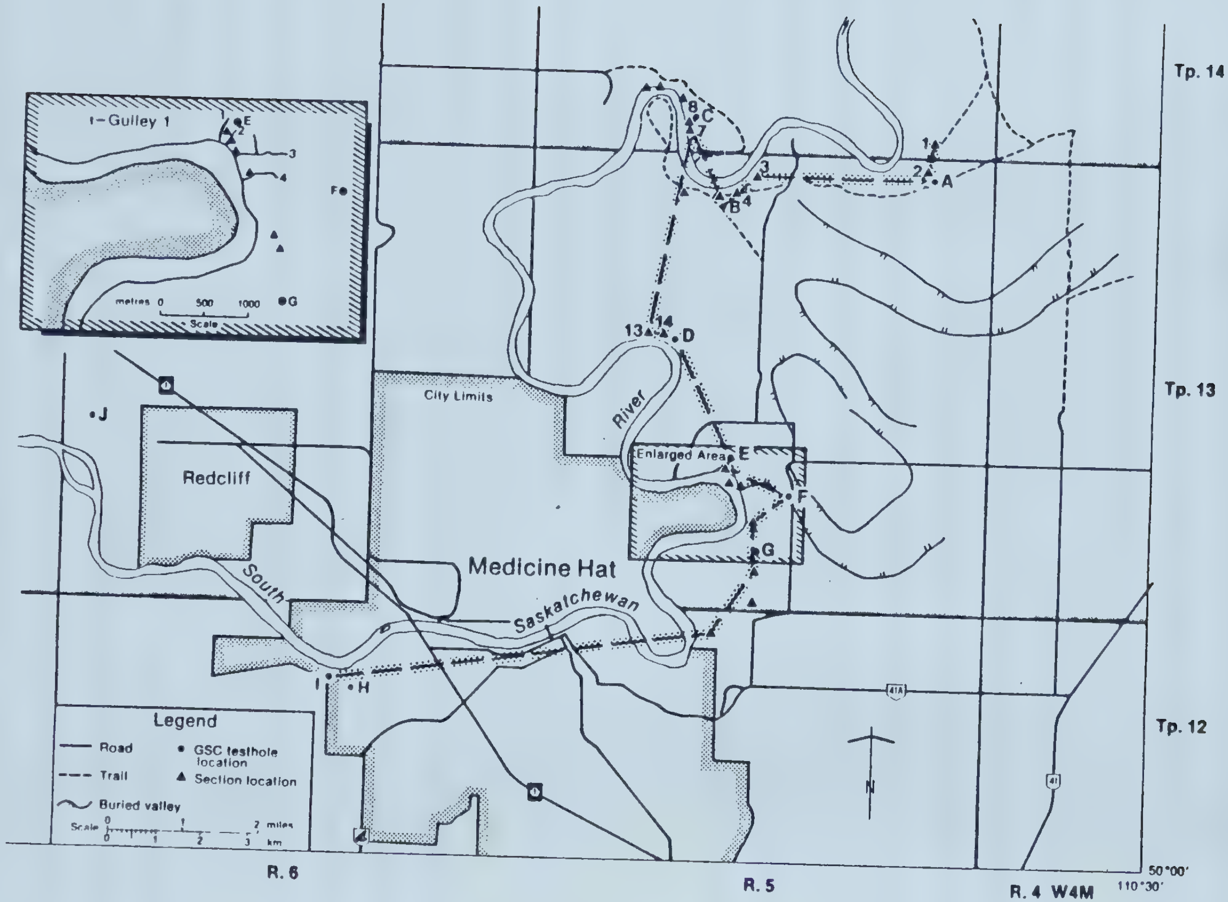


Figure 3.2. Map showing the trace (stipled-dashed line) of the summary cross section sketched on Figure 3.1.

differs from the existing one (Stalker, 1969a, 1970, 1972, 1976a, 1977b).

Formation A consists of a dark grayish brown, clayey silt diamicton. It includes three lithofacies, (i) unlayered diamicton (UD) containing abundant sandstone inclusions, (ii) a thick deposit of deformed stratified diamicton (lithofacies DSD), and (iii) a thin deposit of undeformed tabular interbedded diamicton, sand and silt (lithofacies IDSS-T). Formation A contains material derived from the Canadian Shield and has a sharp basal contact. Its upper contact is an unconformity that is erosional in some places.

Formation B consists of three members. The *lower member* consists of two subunits, the lower of which contains lag gravel and the upper sand that becomes finer upwards. It occurs in a valley that is cut into the top of, or incised through, formation A and marks the unconformity at the top of formation A. This valley, now partially buried, is shown in Figure 3.2 and can be traced on aerial photographs northwards from the north end of Golden Valley Bluff to Evilsmelling Bluff and Mitchell Bluff, where similar sequences of the Empress Formation and formation A and B have been observed in outcrop and testholes (Figure 3.3, in pocket).

The *middle member* consists of two units.

1. The lower unit contains silt and very fine sand, gradationally overlies the lower member, and occurs in the buried valleys on top of the lower member.
2. The upper unit contains diamicton, sand, and silt, which are included in three diamicton and related lithofacies including layered diamicton (LD), stratified diamicton (SD), and tabular interbedded sand, silt, and diamicton (IDSS-T). Its most distinctive characteristics are the dark gray clayey silt diamicton component of Keewatin provenance and the prevalent stratification.

The *upper member* of formation B consists of light yellowish brown sandy silt diamicton that contains material derived from the Canadian Shield. It has a gradational contact with the middle member or has a sharp erosional basal contact. Lithofacies present in this formation include unlayered diamicton (UD), diamicton containing lenses (DCL), and intermittent clast associations (ICA).

Formation C is the surface unit in most of the area. It includes five different discontinuous lithofacies, including (i) interbedded silt and clay that fines upwards into rhythmites; (ii) bedded silt and sandy silt containing paleosols; (iii) lenticular interbedded

diamicton, sand and silt (lithofacies IDSS-L) that occurs in modern alluvial fans; (iv) cross-bedded sand that occurs as infill in depressions on top of formation B; and (v) sand, silt and gravel of the modern South Saskatchewan River valley and its tributaries.

General comments on the lithostratigraphy

The lithostratigraphy in the study area is summarized in detail in Table 3.1 and is shown in cross section in Figure 3.3. It has been defined primarily on the basis of the field relationships between recognizable units or groups of units. Major unconformities and major changes in sediment type were used to delineate stratigraphic units at each outcrop. Where possible, the presence of several lithofacies in a single stratigraphic unit has been used to explain differences in the character of a unit between outcrops, so that correlations could be made. Laboratory analyses have been used to characterize units and in places to aid in correlation. Refer to Appendix A for detailed descriptions of all sections described in the text. Table 3.2 and Figure 3.4 provide a summary of analytical data collected for diamicton units within the major Quaternary formations.

The detail required for lithofacies determination demanded that the nature of contacts be examined closely. This became extremely important for the delineation of major stratigraphic contacts. As the mapping at individual stations proceeded, major unconformities were recognized, in particular, by the presence of erosional surfaces marked by lag gravel and sharp contacts. These had to be distinguished from local unconformities between or within lithofacies deposited during the same event. One major interdiamicton fluvial erosional unconformity has been used within and between outcrops as an aid to correlation. It is therefore necessary to discuss the basis for correlation of fluvial sediment, because river valleys are very restricted features that do not cover the entire landscape. First of all, in the Medicine Hat area, fluvial sediment correlation can confidently be made for the lower member of formation B (Table 3.1), because there is a surface expression to the buried valley that formed during deposition of the sand and gravel of this member. The outline of this valley is shown in Figure 3.2. It can be traced on aerial photographs from Golden Valley Bluff northwards to Evilsmelling and Mitchell Bluffs. The same stratigraphic sequence (formation A overlain by the lower and middle members of formation B) is evident in each of these buried valley exposures. Elsewhere,

Formation	Member	Facies	Granulometry			Clay Mineralogy					Coarse Sand Lithology			
			% + sand	% ● clay	N	% kaol	% ill	% mont	% chl	N	% Loc	% CS	% carb	N
B	upper	ALL	* $\frac{38}{3}$	$\frac{28}{2}$	25	$\frac{10}{4}$	$\frac{33}{7}$	$\frac{51}{9}$	$\frac{5}{3}$	29	$\frac{18}{8}$	$\frac{53}{9}$	$\frac{29}{11}$	25
		UD	$\frac{38}{3}$	$\frac{28}{2}$	20	$\frac{11}{4}$	$\frac{35}{7}$	$\frac{48}{9}$	$\frac{6}{3}$	20	$\frac{18}{7}$	$\frac{51}{8}$	$\frac{31}{10}$	17
		UD?	$\frac{40}{2}$	$\frac{27}{2}$	5	$\frac{10}{3}$	$\frac{30}{7}$	$\frac{55}{9}$	$\frac{4}{2}$	5				
B	middle	ALL	$\frac{20}{11}$	$\frac{38}{7}$	76	$\frac{9}{5}$	$\frac{38}{8}$	$\frac{45}{10}$	$\frac{7}{4}$	66	$\frac{22}{14}$	$\frac{36}{12}$	$\frac{42}{13}$	73
		LD. LD?	$\frac{15}{7}$	$\frac{41}{6}$	28	$\frac{7}{5}$	$\frac{37}{6}$	$\frac{48}{9}$	$\frac{8}{3}$	29	$\frac{27}{16}$	$\frac{36}{13}$	$\frac{37}{15}$	26
		LD	$\frac{16}{8}$	$\frac{41}{4}$	19	$\frac{9}{5}$	$\frac{37}{7}$	$\frac{48}{10}$	$\frac{7}{4}$	18	$\frac{28}{16}$	$\frac{34}{12}$	$\frac{39}{14}$	15
		IDSS	$\frac{23}{21}$	$\frac{36}{10}$	13	$\frac{8}{5}$	$\frac{31}{4}$	$\frac{55}{6}$	$\frac{6}{3}$	8	$\frac{22}{17}$	$\frac{35}{11}$	$\frac{43}{11}$	15
		SD	$\frac{25}{8}$	$\frac{36}{5}$	20	$\frac{13}{5}$	$\frac{45}{8}$	$\frac{37}{9}$	$\frac{6}{3}$	15				
A	------	ALL	$\frac{17}{8}$	$\frac{41}{6}$	51	$\frac{13}{3}$	$\frac{36}{6}$	$\frac{47}{9}$	$\frac{4}{4}$	39	$\frac{23}{11}$	$\frac{40}{12}$	$\frac{36}{10}$	26
		UD	$\frac{16}{8}$	$\frac{41}{6}$	30	$\frac{12}{3}$	$\frac{37}{7}$	$\frac{46}{10}$	$\frac{5}{3}$	21	$\frac{26}{9}$	$\frac{33}{10}$	$\frac{41}{7}$	15
		DSD	$\frac{17}{8}$	$\frac{43}{8}$	6	$\frac{13}{1}$	$\frac{34}{5}$	$\frac{51}{8}$	$\frac{2}{3}$	5	$\frac{24}{3}$	$\frac{48}{1}$	$\frac{28}{4}$	3

Table 3.2. Summary of analytical parameters for major lithostratigraphic units by lithofacies

+ sand (0.0625 to 2 mm)
N: number of samples analyzed
kaol: kaolinite
ill: illite
mont: montmorillonite
chl: chlorite

● clay (< 0.0039 mm)
loc: local (sandstone, siltstone, shale, coal, ironstone, chert)
CS: Canadian Shield material (granites and mafics)
carb: carbonate (limestone, dolostone, dolomitic siltstone)
* $\frac{\text{average}}{\text{standard deviation}}$
? indicates an uncertain lithofacies classification

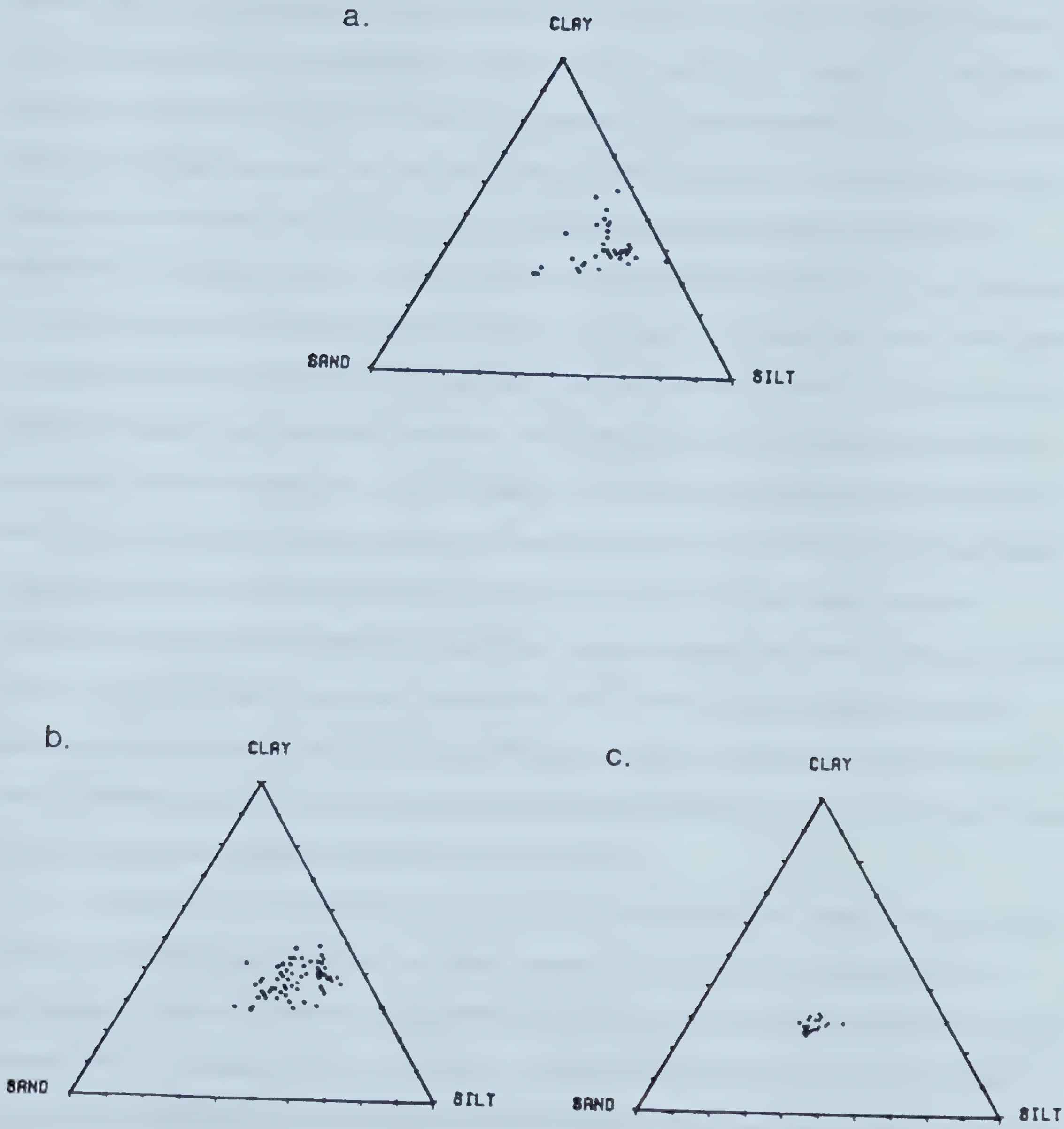


Figure 3.4. Ternary diagrams showing the distribution of texture (<1mm), clay minerology and coarse sand lithology for the diamicton components of each stratigraphic unit in the Medicine Hat area.

formation B can be correlated primarily on the basis of its stratigraphic position.

The correlation of this fluvial unconformity is fundamental to the stratigraphy developed within this study and is based on the following assumption. Observations on the present landscape in southern Alberta delineate contiguous topographically low areas that in many places follow former valley systems that are commonly partially or completely infilled with sediment. The thick Quaternary deposits in southeastern Alberta are preserved in topographically low areas on the underlying pre-Pleistocene surface. Most of these bedrock depressions have been extensively traced by drilling during groundwater exploration (Westgate, 1968; Carlson, 1970) and have been interpreted to be preglacial river valleys, based on their morphology and the presence of basal sand and gravel beds within them that contain no material derived from the Canadian Shield. It is likely that as any glacier retreated from the region many of the valley systems that existed before that particular glacial advance were still represented to varying degrees by depressions in the new glacial topography. As meltwater drained the glacier, and as the normal interglacial drainage pattern re-established, rivers and streams would follow these low areas. Therefore, through the Quaternary, many river valley systems, or parts of them, would be re-used, and the higher intervening areas that were commonly underlain by bedrock plateaus would be essentially untouched. This hypothesis is supported by the fact that most Quaternary sediment that occurs outside of buried valley systems in the study area is thin and very rarely contains evidence of fluvial activity.

Therefore, as a stratigraphic framework is developed and traced in this area, it is within buried valley systems that the thick sediment sequences are invariably found. Furthermore, much of the fluvial sediment found within the valley-fill sequences records a fluvial event or events that, in most places, followed these courses. Therefore, the stratigraphic position of sediment from major fluvial events can be used as a primary tool in correlation in the area.

The stratigraphic relationships between units and unconformities found in various outcrops in the Medicine Hat area provide the foundation for formation definition. Table 3.1 summarizes the lithostratigraphic details, whereas the following text highlights formation descriptions and correlations at localities where relationships are best seen or where variation occurs. Where reference is made to a unit or units at a specific site, the

detailed description is contained in Appendix A. Testhole descriptions are from Stalker and Wyder (1983) and from their unpublished sidewall sample descriptions. It is important to note that with the exception of IDSS-L, the basal contacts of diamicton and associated lithofacies are horizontal, lithofacies are laterally extensive and lateral lithofacies transitions were not observed.

B. Stratigraphic Units

In the following section, the general characteristics and distribution for each stratigraphic unit above the clearly defined Upper Cretaceous units are described.

C. Empress Formation

This is stratigraphically the lowest formation of Quaternary sediments and directly overlies Cretaceous units. The Empress Group was defined by Whittaker and Christiansen (1972) to include all sediment that occurs between the top of the Cretaceous units and the base of the oldest till unit in the area. It has not been possible to define units in this formation because sub-units are not regionally mappable. Therefore, the Empress Formation is used instead of the Empress Group, and it is informally subdivided into members. The top of the Empress Formation is defined by a sharp change in sediment type from silt, clay, sand, and gravel to diamicton.

Lower Member

The lower member of the Empress Formation is predominantly a sandy clast-supported gravel that directly overlies Cretaceous units. Its basal contact has not been observed in outcrop in the Medicine Hat area because it occurs below river level or is covered by slump blocks. However, it has been detected in testholes GSC73.GV, GSC73.TC, GSC69-7, GSC69-2 and GSC69-4 (refer to Figure 3.3), where its basal contact is sharp (Fig. 3.5) and unconformable. The upper contact is sharp, as indicated by testhole geophysical logs (Fig. 3.5). The thickness of the lower member, measured from testhole logs, varies from 3 to 7.6 m. Its identification is based on the following:

1. Lack of material derived from the Canadian Shield.
2. Its stratigraphic position above Cretaceous units and below all other Quaternary units.

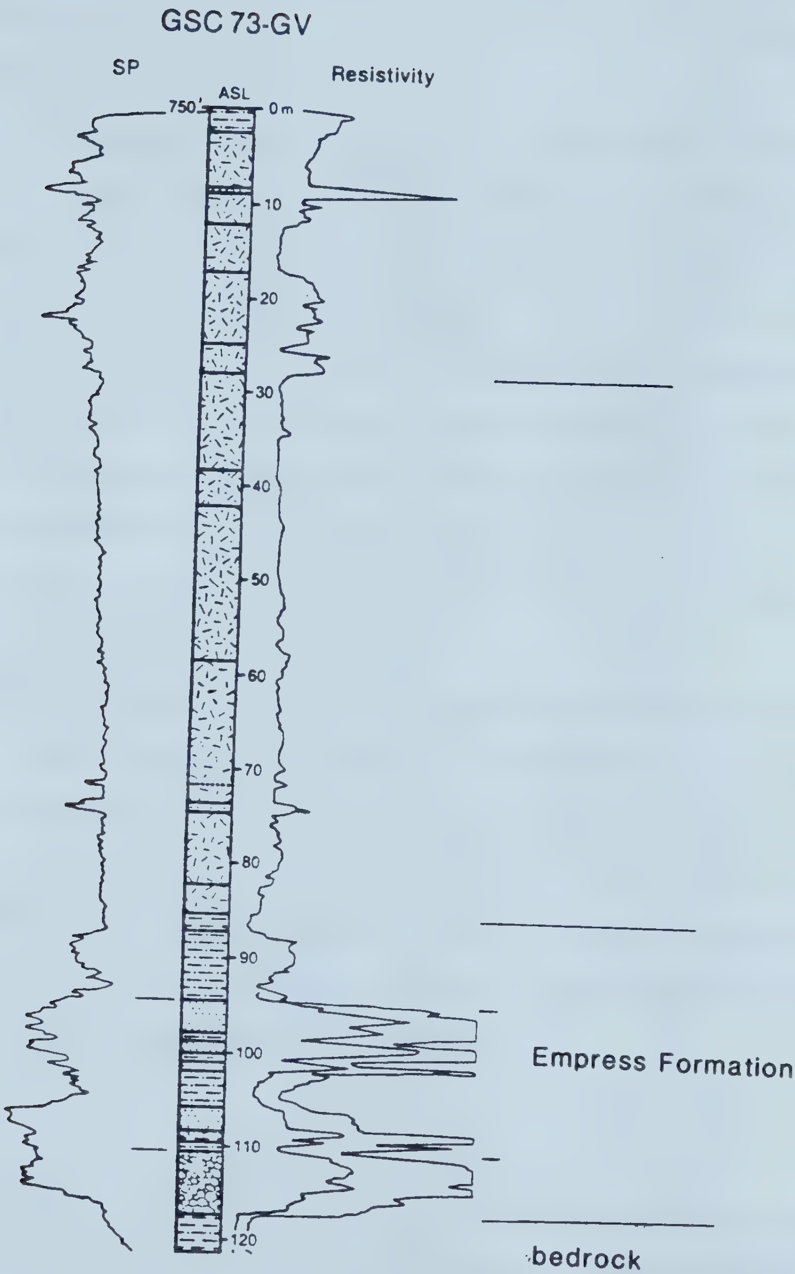


Figure 3.5. Electric-logs for testhole GSC73.GV (located on Figure 3.3).
Note the sharp contact between the middle and lower members of the Empress Formation.

Middle Member

The middle member of the Empress Formation is identified on its absence of material derived from the Canadian Shield and its stratigraphic position. It has a sharp basal contact with the lower member (Fig. 3.5).

Two major lithofacies have been identified in the middle member. One that is composed of very fine sand, silt and clayey silt and the other is sandy (Plate 3.1).

1. A stoneless, very fine sand, silt and clayey silt lithofacies that has even parallel bedding and is dark gray. Individual beds are laminated and range from 5 to 30 cm thick. This lithofacies underlies most exposures of the sandy lithofacies and is interbedded with it in many places. It is best exposed at the east end of Mitchell Bluff (Fig. 1.2), where it is approximately 5.4 m thick, occurs underlying and interbedded with the cross-bedded sandy lithofacies, and extends for more than 50 m laterally. A 6.5 cm diameter tree trunk was found in the growth position within this lithofacies at the north end of Golden Valley Bluff, near gully number 2 (Fig. 1.2).

2. A sandy lithofacies consisting of medium to fine sand that is devoid of material derived from the Canadian Shield. Climbing ripple beds occur interbedded throughout most of this lithofacies, and cross-bedding with scours up to 1 m deep (Plate 3.2) are common. Many scours are infilled with sand containing abundant silt and clay intraclasts and scattered wood fragments (Plate 3.3). This sandy lithofacies is up to 12.4 m thick and gradationally overlies the silty clay lithofacies of the middle member. It is best exposed along the north end of Golden Valley Bluff and at the east end of Mitchell Bluff.

Upper Member

The upper member of the Empress Formation is a silt and clay unit that fines upwards from the middle member (Plate 3.1). At its base it is a weakly laminated to structureless silt and sandy silt lithofacies, with minor sand beds that grade upwards through parallel laminated silt, fine sand and minor clay beds, to a cap of up to 1 m of rhythmically bedded silt and clay (Plate 2.5). Load structures occur along bedding planes throughout the lower part of this member (Plate 3.4). Small gravelly lenses containing pebbles derived from the Canadian Shield are also common.

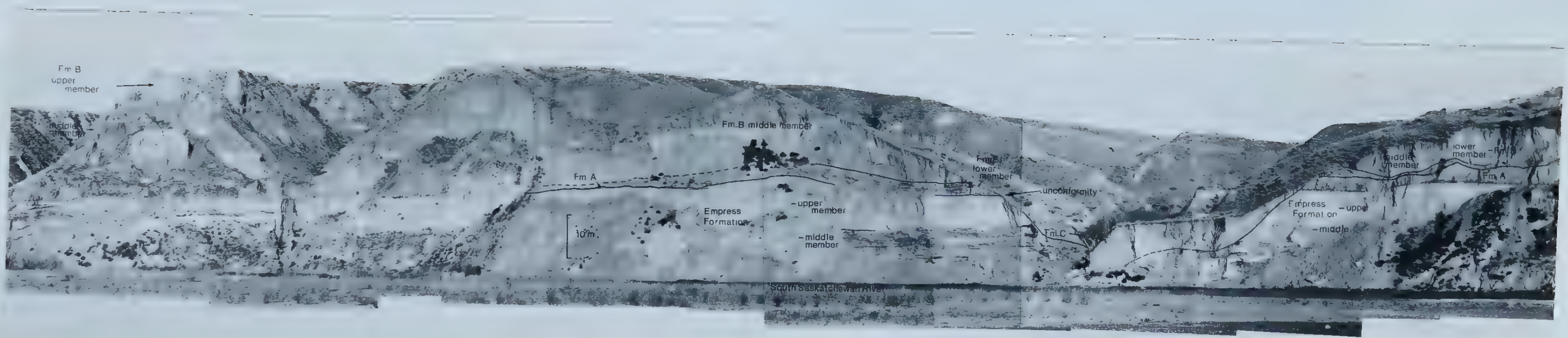


Plate 3.1. The north end of Golden Valley Bluff exposes the middle and upper members of the Empress Formation, a thin discontinuous remnant of formation A and most of formation B. The scale is just left of centre.

Plate 3.2. The sandy lithofacies of the middle member of the Empress Formation at the north end of Golden Valley Bluff. The arrow in the upper left points to a silty bed. This exposure is 7 m high.

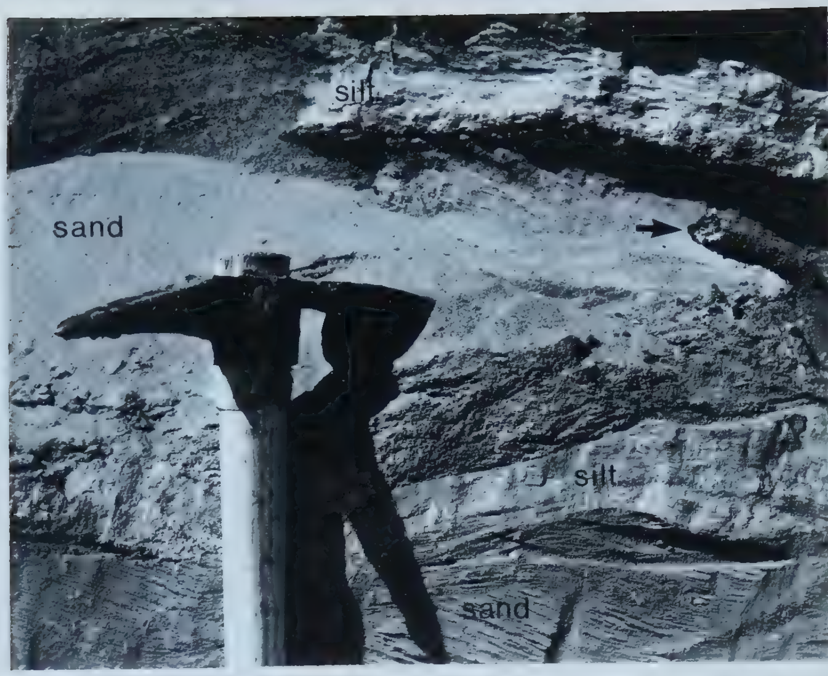


Plate 3.3. A heavily mineralized twig (arrow, upper right) within the sandy lithofacies of the middle member of the Empress Formation. About 30 cm of the pick are shown.

Plate 3.4. Load structures (located along the bedding plane in the centre of the photograph) within the sandy silt lithofacies of the upper member of the Empress Formation.

The top of the upper member is easily recognized because it contains the only fine rhythmically bedded silt and clay unit observed in outcrop in a stratigraphic position anywhere below the surface diamicton (upper member of formation B) within the area A similar silt and clay unit occurs in testholes GSC69-1, GSC69-2, GSC69-3, GSC69-4, GSC69-5, GSC73.GV and GSC73.TC (Fig. 3.3). This member is less than 6 m thick and is best exposed at the north (Plate 3.1) and south ends of Golden Valley Bluff and at the east end of Mitchell Bluff (Fig. 1.2).

D. Formation A

Formation A consists of grayish brown (2.5Y 5/2 dry) to very dark grayish brown (2.5Y 3/2 dry) clayey, silt diamicton (Fig. 3.6 and Table 3.2). In places a conspicuous brownish yellow stain follows major vertical joints, penetrating as much as 5 mm into the matrix (Plate 3.5). Formation A contains material derived from the Canadian Shield. It has been identified at two outcrops with certainty (Golden Valley Bluff and Island Bluff; Fig. 1.2).

Recognition and correlation of formation A are based on its stratigraphic position, distinctive appearance, texture, and electrical-log character (Table 3.1 and Fig. 3.5). Formation A is the least documented diamicton-bearing formation and provides the most potential for errors in correlation. Therefore, it is described at its two best outcrops individually.

1. Golden Valley Bluff

The lower contact of formation A is associated with a fracture zone that varies from less than 1 cm (Plate 2.4) to 1 m thick (Plate 2.5) along the north end of Golden Valley Bluff (Fig. 1.2). Scratches are common on bedding-plane surfaces within and adjacent to the contact zone. Figure 3.7 summarizes measurements of these lineaments for the north end of Golden Valley Bluff, where it is best exposed. Overlying this contact at the north end of Golden Valley Bluff (DNP78-14) about 8 m of the basal part of formation A are exposed (Plate 3.1). Here the formation consists of unlayered diamicton that contains large inclusions of friable silty sandstone (larger than 2 by 2 m; see Plate 3.6).

In the central part of Golden Valley Bluff (Plate 1.1, DNP78-13, Fig. 3.3) formation A is more than 27 m thick and is composed of three lithofacies. The lower part of the unit

a.

b.

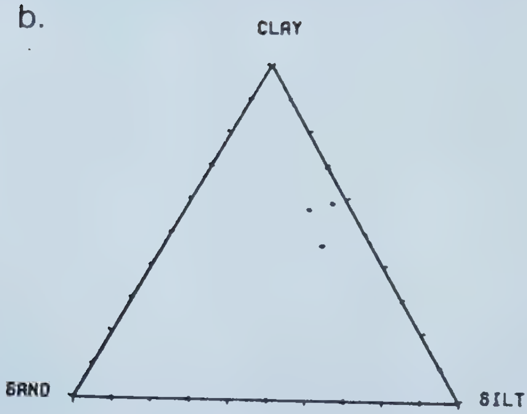


Figure 3.6. a. Ternary diagram showing the grain-size distribution (<1mm fraction) of formation A diamicton. b. Ternary diagram showing the grain-size distribution (<1 mm fraction) of formation A diamicton within 1 metre of its base along the north end of Golden Valley Bluff.

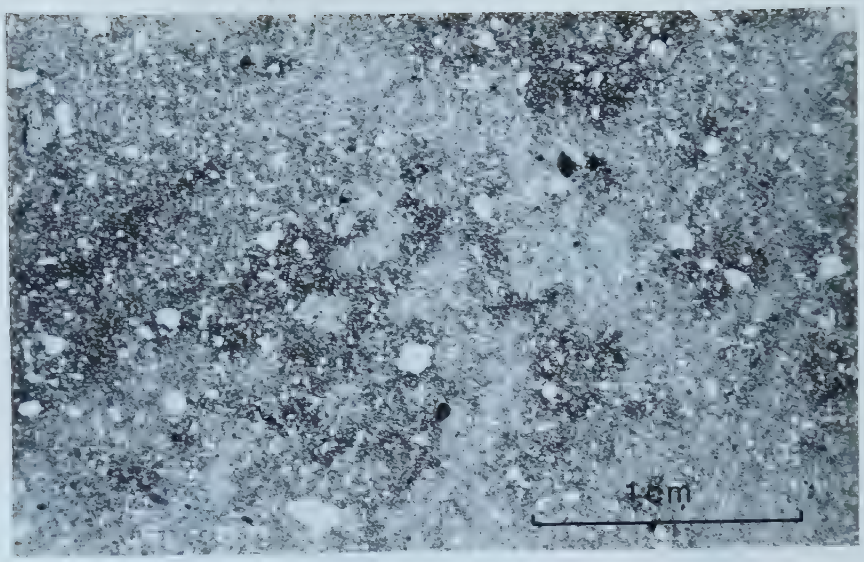


Plate 3.5. Photomicrograph showing the character of formation A diamicton. The dark coloration is stain that occurs near major joints throughout much of the unit.

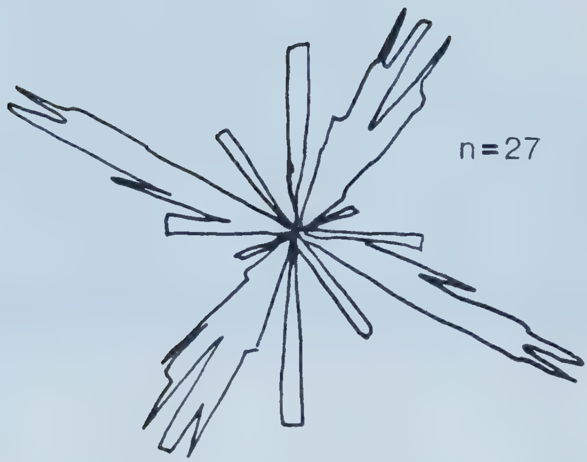


Figure 3.7. Rose diagram (10 degree moving average) showing the orientation of scratches and drag fold axes (025) found along the basal contact zone of formation A at the north end of Golden Valley Bluff.

Plate 3.6. A large deformed sandstone block (arrow) within formation A diamicton in gully number 4 at the north end of Golden Valley Bluff. The outcrop is about 25 m high.

is covered, but at the base of the exposure there is a thick deposit of deformed stratified diamicton (DSD). This lithofacies contains abundant deformed stratified silty sandstone inclusions that occupy 5 to 10 percent of its volume (Plate 3.6). It also has soft-sediment deformation structures (Plate 2.18) that are highlighted by slight differences in colour and texture, which are difficult to detect on close examination. The thickness of lithofacies DSD in formation A ranges from 10 to 20 m. Overlying it is a thin capping of 1 to 3 m of relatively undeformed tabular interbedded sand, silt, and diamicton (lithofacies IDSS-T, Plate 2.18).

The upper surface of formation A can be traced in outcrop for about 600 m along the north end of Golden Valley Bluff from about 100 m south of gully number 4 (Figure 1.2 and Plate 3.7), northwards to gully number 1 (Fig. 1.2). Over this distance, formation A thins to a discontinuous, 0.5-m-thick unlayered (UD), fractured remnant that is clayier and less sandy (Fig. 3.6 b) than the diamicton in the rest of the unit (Figure 3.6 a). It contains smeared bands of clay that appear to have been derived from the underlying upper member of the Empress Formation. Similar thin remnants of formation A are exposed at the east end of Mitchell Bluff.

2. Island Bluff

At the southeast end of Island Bluff (DNP-78-4, Fig. 2.2), 13.2 m of formation A crops out. The abundant sandstone inclusions present at Golden Valley Bluff are absent and it is composed entirely of lithofacies UD. There is a horizontal band in the centre of the formation that thickens to the southeast and forms an apparent contact within the unit (Plate 3.8). This silt band is deformed and drawn out (Plate 3.9) and forms the base of a wedge of formation A diamicton that is thickest at DNP78-4 and thins to the southeast. Contacts within formation A have not been observed elsewhere.

Two other possible occurrences of formation A have been identified. Formation A is poorly exposed or possibly not exposed at all at Evilsmelling Bluff (Fig. 2.2; DNP79-11, unit 1). However, a nearby testhole, GSC69-3 (Figure 3.3), intersects about 5 m of a diamicton with similar textural and electrical-log characteristics in the same stratigraphic position.

3. At Bain Bluff, formation A may be exposed at DNP78-9, but the outcrop is too poor to be sure. Testhole GSC69-4, which was drilled behind this bluff (Figure 3.8), intersects

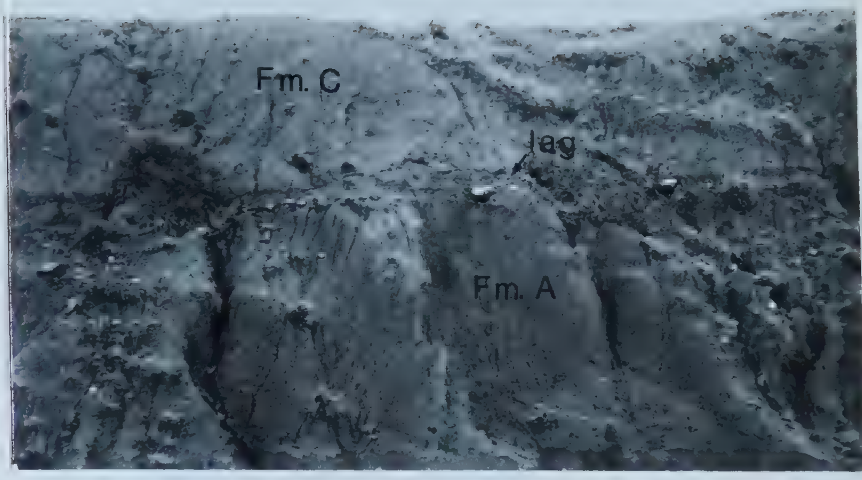


Plate 3.7. The upper contact of formation A, exposed in gully number 4, is marked by an erosional contact with lag boulders along it. In this 7 m high outcrop it is overlain by formation C sediment.

Plate 3.8. Formation A at the east end of Island Bluff. Note the apparent contact (arrow) within it and the location of Plate 3.9 (rectangle).

Plate 3.9. A portion of the deformed and faulted silt band (lighter gray) within formation A unlayered diamicton (lithofacies UD, dark gray) at the east end of Island Bluff. The pick is 95 cm long.

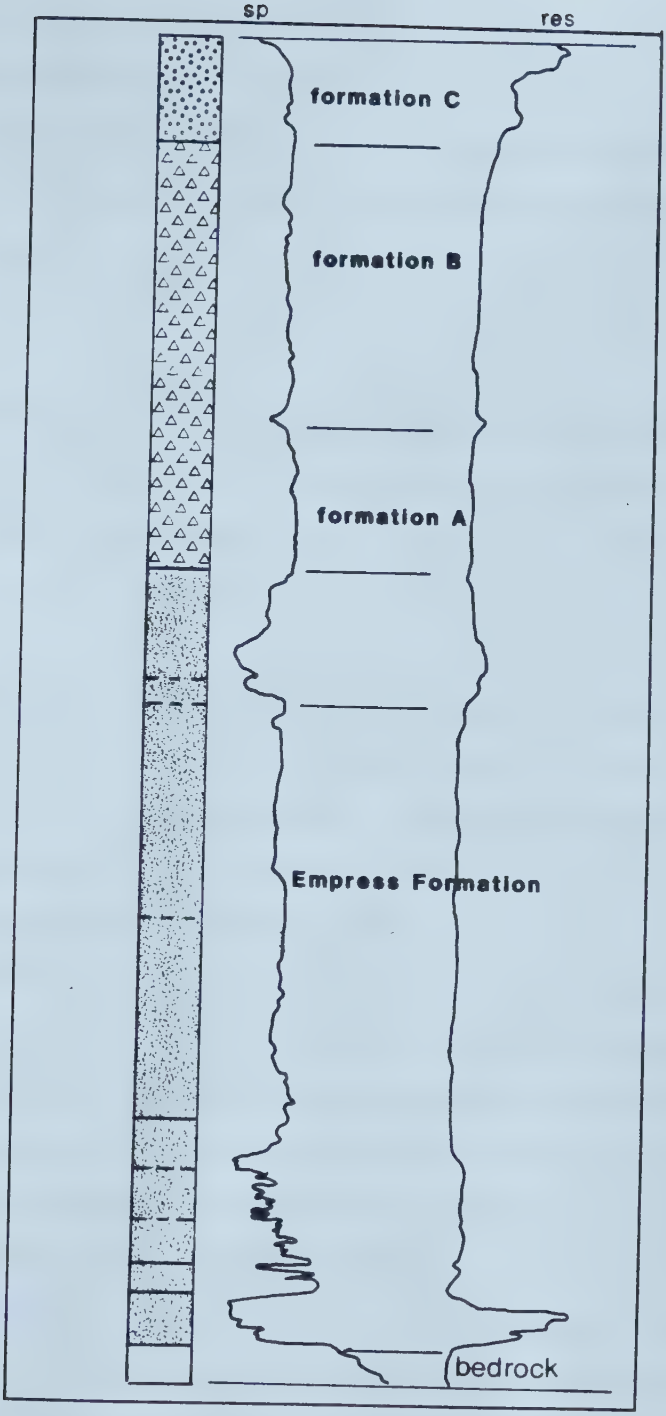


Figure 3.8. Electric-logs for testhole GSC69-4. 'SP' and 'res' label spontaneous potential and resistivity logs respectively. The triangular pattern represents predominantly diamicton; the stiples - sand, silt, and gravel; the open circles are silt and sand. The horizontal lines between the log curves are formation contacts.

diamicton at this stratigraphic position, however, it is much sandier than elsewhere. Unfortunately the electrical logs for this testhole are poor so that correlation is based mainly on stratigraphic position. In addition, there is also the possibility that this diamicton is part of the middle member of formation B, although its consistent texture is not typical for the latter diamicton.

E. Formation B

Formation B occurs between the unconformity on top of formation A and the surface sediments of formation C. It is composed of three distinctive members, of which the middle and upper are the thickest.

Lower Member

The lower member of formation B is predominantly composed of sandy and gravelly lithofacies. Where the gravel lithofacies is present, it is 10 to 70 cm thick, sandy to cobbly and overlies thin remnants (less than 1 m thick) of formation A and the upper member of the Empress Formation. It grades upwards from an abrupt lower contact into a horizontally or cross-bedded sandy lithofacies (Plate 3.1).

At the north end of Golden Valley Bluff (Plate 3.1 and Fig. 2.2) this gravel can be traced along the top of formation A southwards to DNP78-13, where it is about 50 m higher in elevation (Fig. 3.3). At the latter location, the lower member is a 0.5 to 1 m thick, medium to coarse grained, cross-bedded sand with rare pebbles and synformal deformation. At the north end of Golden Valley Bluff (Plate 3.1), Mitchell Bluff East, testhole GSC73-TC and possibly testholes GSC69-3 and 69-5 (Fig. 3.3), the lower member overlies thin remnants (less than 1.5 m thick) of formation A. Elsewhere along these two exposures it directly overlies the silt and clay of the upper member of the Empress Formation. Therefore, the base of formation B is interpreted to overlie an erosional unconformity, with the cobbles and gravel forming a lag deposit.

A buried valley system is shown in Figure 3.2. The position of the valley walls was determined from aerial photographs and closely agrees with the outcrop limits of the gravel described above in the lower member of formation B. This valley has been traced to the east end of Mitchell Bluff (Fig. 3.1) and to near Evilsmelling Bluff, where the sand and

gravel of the lower member are in the same stratigraphic position.

Part of the lower member of formation B is exposed at Evilsmelling Bluff (DNP79-14, unit 1, Plate 3.10). There it is a fining upwards sequence from medium to silty sand.

At Island Bluff (Fig. 2.2; DNP78-4, unit 4), the lower member of formation B is composed of 5 to 10 cm of well sorted, fine sandy gravel that overlies about 70 cm of structureless sandy silt and more than 6.9 m of formation A.

At Bain Bluff (DNP78-9, units 2 and 3) the lower member of formation B consists of 1.8 m of bedded sandy gravel that grades upwards into 3.8 m of unsorted, unbedded coarse gravel (Plate 3.11). In nearby testhole GSC69-4, at 51.8 m (Fig. 3.3), a 1-m-thick clay bed occurs between beds of diamicton of different texture at the same stratigraphic position. This clay bed is tentatively correlated with the lower member of formation B.

Middle Member

The middle member forms about 40 percent of the volume of formation B. It is composed of two units.

1. The lower unit contains thickly bedded silty sand that fines upwards from a gradational basal contact to weakly laminated sandy silt with minor thin (less than 5 cm), fine to medium grained sand beds. It is confined to the buried valley (Fig. 3.2) that is cut into the top of formation A at Golden Valley Bluff North (DNP79-17, unit 7; and DNP79-19, unit 7; Plate 3.1) and at the east end of Mitchell Bluff (the upper part of unit 7, DNP80-53).
2. The upper unit contains diamicton, sand, and silt that is composed of three lithofacies. In most places, the diamicton of this unit has a clayey silt texture (Fig. 3.9 and Table 3.2) and has a well developed blocky structure (1^3 to 4^3 cm blocks), a distinctive dark grayish brown (2.5Y 4/2 dry) colour and a dark red (2.5YR 3/6 dry) joint face stain. The entire member is characterized by its distinct stratification. The basal contact of this unit is sharp where it directly overlies the lower member of formation B (DNP79-14, Plate 3.10; DNP79-17 and 19).

The lithofacies of this unit include the following:

1. Layered diamicton (lithofacies LD), which is the predominant lithofacies in this member. The banding is irregular, with internal deformation such as attenuated structures and

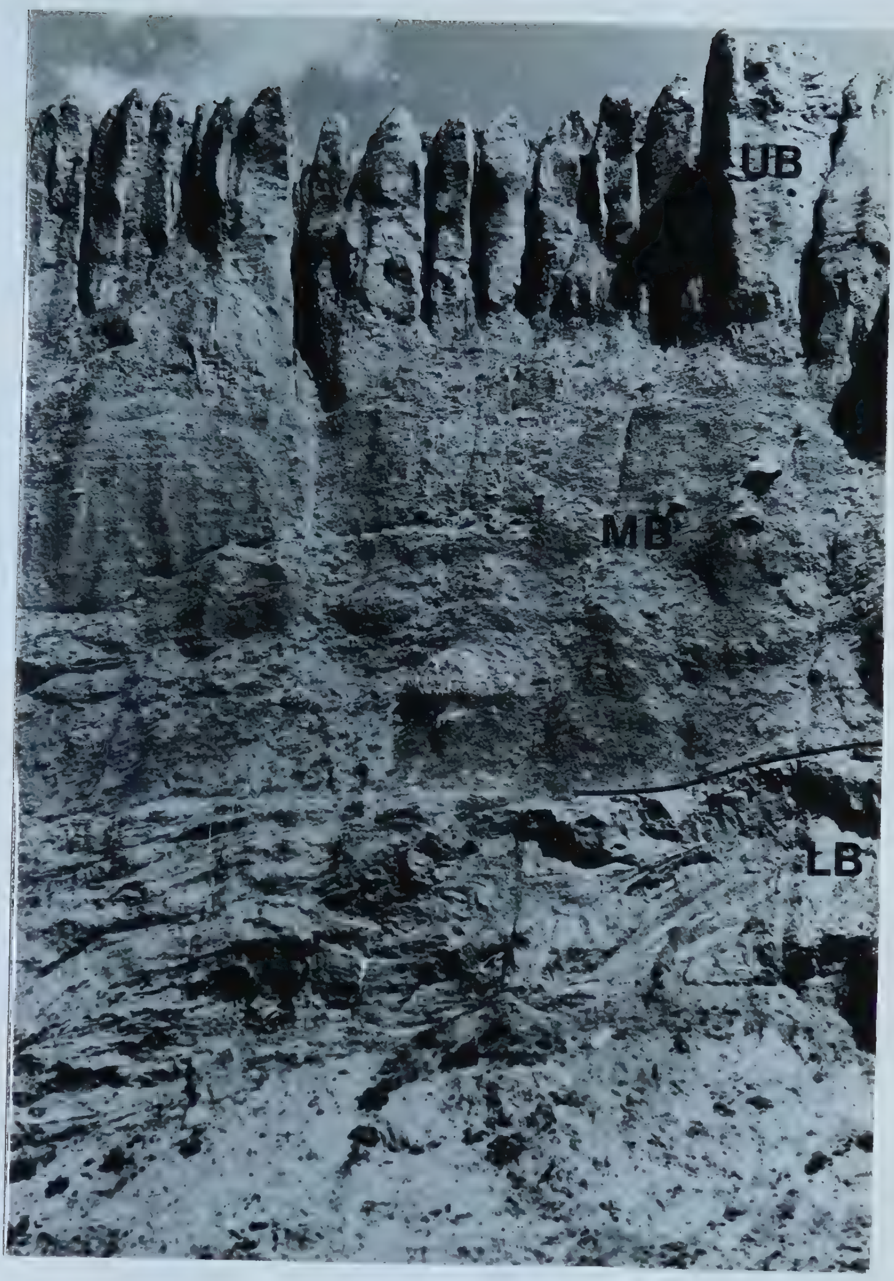


Plate 3.10. Evilsmelling Bluff about 75 metres north of DNP79-14. Note the sharp contact along the base of the diamicton of the middle member of formation B (MB, black line) and the deformation within the sandy lower member of formation B (LB). The middle member of formation B (MB) is composed of layered diamicton (lithofacies LD). Note the gradational contact with unlayered diamicton (lithofacies UD) of the upper member of formation B (UB). About 25 m of outcrop are shown.

Plate 3.11. The lower sandy gravel member of formation B at Bain Bluff. Note the upward gradation form horizontally bedded sand and gravel to unbedded, poorly sorted sandy gravel.

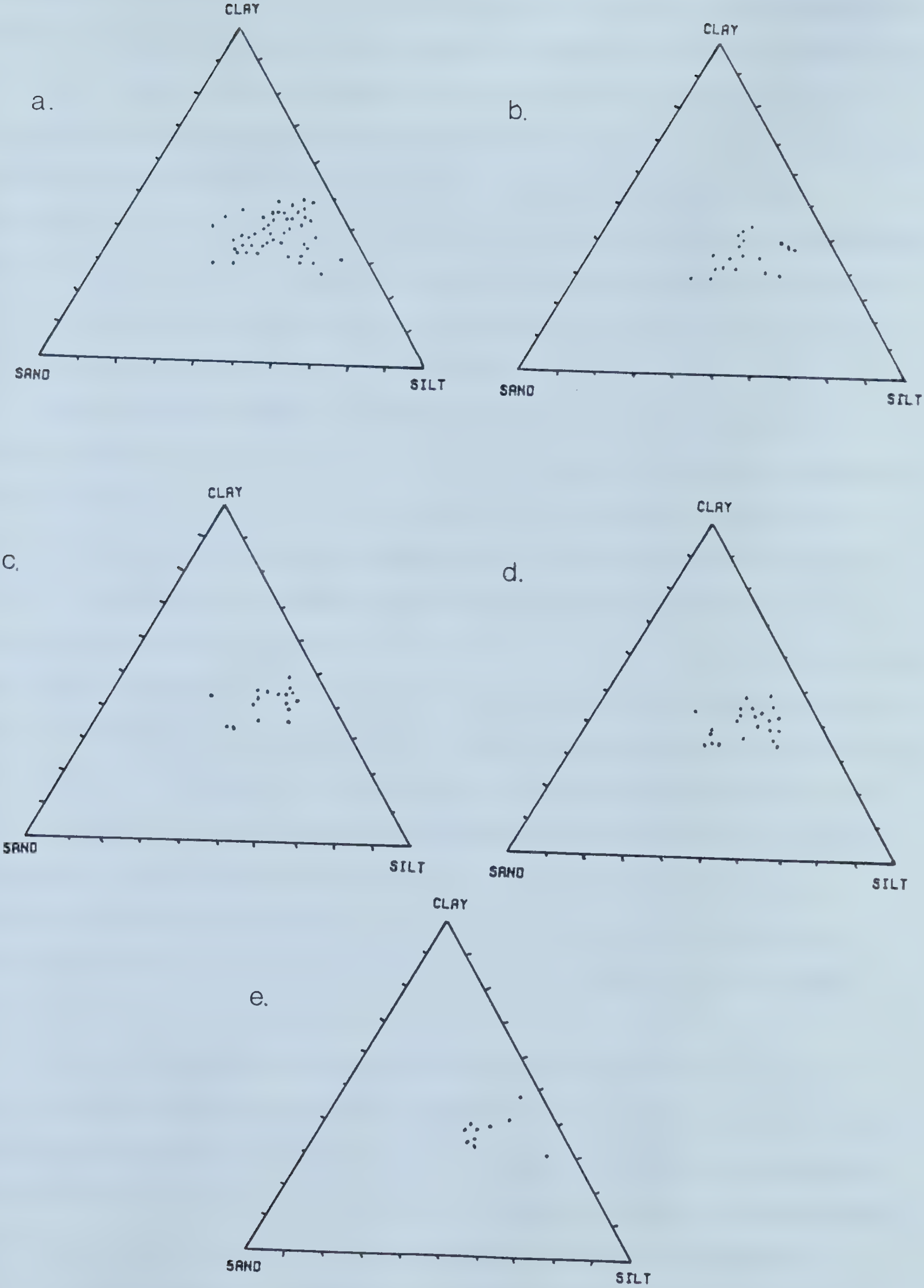


Figure 3.9. Grain-size distribution for diamicton in each lithofacies within the middle member of formation B. a. all lithofacies b. lithofacies SD. c. lithofacies LD. d. lithofacies LD and possible LD samples. e. lithofacies IDSS-T.

recumbent folds common. It is well exposed along most of the central and southern parts of Golden Valley Bluff (Plate 1.1) and at Evilsmelling Bluff (DNP79-11, unit 6; Plate 3.10).

2. Tabular interbedded diamicton, sand, and silt (lithofacies IDSS-T) is best exposed at the south end of Golden Valley Bluff (Plate 3.12 and at DNP82-100, units 6 and 7) where it falls outside of the buried valley found at the north end of the bluff. Here it occurs on top of a thick deposit of formation A (thicker than 27 m). It directly overlies the thin discontinuous silty sand unit of the middle member of formation B. The silty sand and sand beds or lenses within this unit contain internal silt laminae, have sharp basal contacts, are discontinuous, and vary in thickness from 0.5 to 20 cm. No rip-up clasts were observed within them. Diamicton beds range from 0.5 to 20 cm thick and have sharp basal contacts.

Lithofacies IDSS-T is also well exposed in the central part of Mitchell Bluff (DNP78-8, units 2, 3, and 4), where it is 12.2 m thick (Figure 2.8). At the southeast end of Island Bluff (DNP78-4, units 6 to 11), lithofacies IDSS-T is present as a sequence of relatively thick sandy silt and diamicton beds (Plate 1.2). Three major diamicton beds, 0.7, 1.5 and 3.1 m in thickness, are present. They contain discontinuous beds and/or lenses of silty sand that are generally less than 2 cm thick, have no discernible internal structure, and have only minor deformation along contacts. Between the thicker diamicton beds are silty sand units that have wavy basal contacts. The lowest of these beds (unit 7, DNP78-4) is up to 45 cm thick, inversely graded in its basal 20 cm, normally graded in the centre of the unit, and capped by 15 cm of silt containing scattered stones. The upper silty sand beds (units 9 and 11, DNP78-4) are weakly bedded to cross-laminated with few stones.

3. Stratified diamicton, lithofacies SD, is best exposed along the top of the middle member at Evilsmelling Bluff (DNP79-11, unit 7, Plate 2.11; DNP79-14, unit 3; Plate 2.12), where it reaches a thickness 4 m.

The lateral relationships between diamicton lithofacies within this unit were not observed due to deformational disruptions. However, each lithofacies commonly extends tens to hundreds of metres. This unit occurs in all outcrops in the area, but because it is composed of three lithofacies, it has an inconsistent appearance and inconsistent physical properties Fig. 3.4 and Table 3.2). This inhomogeneity contrasts with the relatively consistent physical character of diamicton in the upper member of formation B and to a lesser extent to that of formation A and has been used as an aid in correlation, especially in

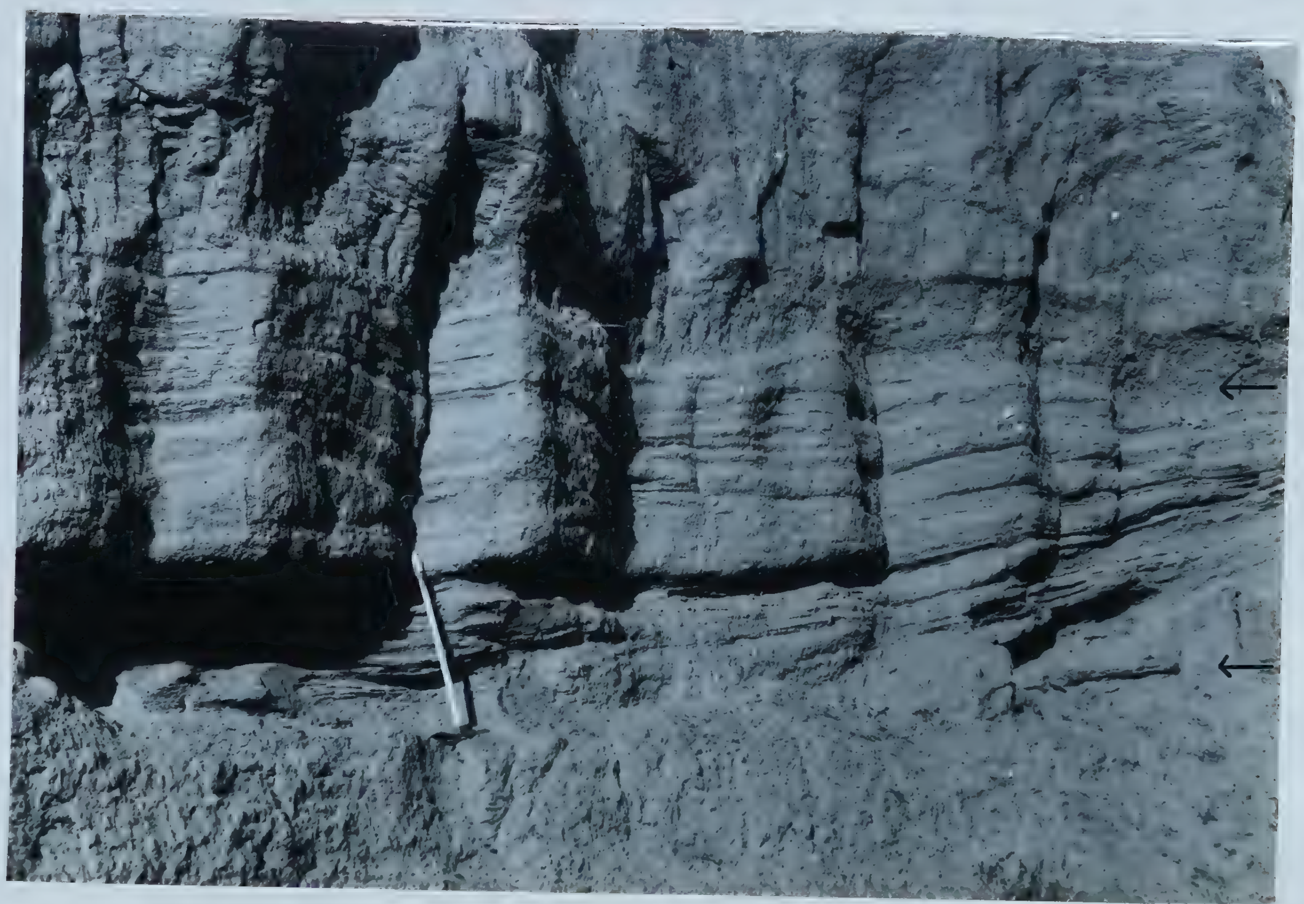


Plate 3.12. Lithofacies IDSS-T (tabular interbedded diamicton, sand, and silt), shown here between the arrows, within the middle member of formation B at Golden Valley Bluff. The dark gray, recessive, horizontal bands are composed of diamicton and the lighter gray bands are sand containing abundant diamicton clasts. In this example, IDSS-T is composed of more than 50 percent sand.

the subsurface.

Nine kilometres to the southwest, testholes GSC69-6 and GSC69-7 (Fig. 3.3) clearly show a fine to medium grained sand that is 7 m thick in GSC69-6 and 18.9 m thick in GSC69-7, directly underlying the uppermost formation B diamicton.

In GSC 69-6 (Fig. 3.3), this sand bed overlies a 5.5 m thick unit that is confidently interpreted from electric-logs and litholog descriptions to be stratified diamicton and is correlated with the middle member of formation B. In testhole GSC69-7, a much thicker sand overlies diamicton that is interpreted from electric-logs to be the stratified middle member of formation B.

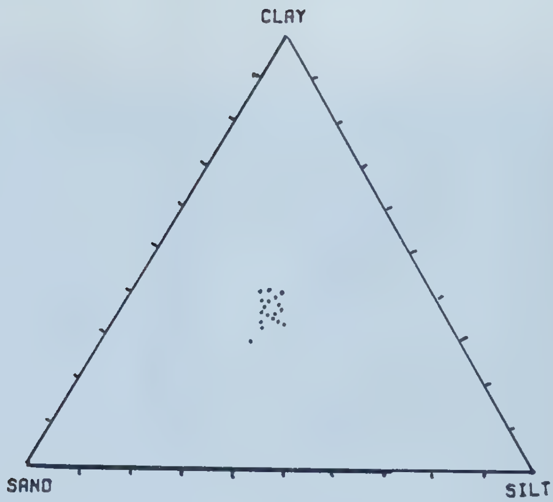
Upper Member

The upper member of formation B contains sandy (Fig. 3.10 and Table 3.2), light yellowish brown (2.5Y 6/4 dry) diamicton that has distinctive, large (1 by 2 m by thickness of unit) columnar jointing on cliff exposures. It contains material derived from the Canadian Shield, forms the surface diamicton in the area, and occurs in most outcrops. At Evilsmelling Bluff (DNP79-11, Plate 2.11, and DNP79-14), the contact between the middle and upper members of formation B is gradational. However, elsewhere its basal contact is a sharp, planar unconformity (Plates 1.1 and 2.9). Deformation within formation B sediments is common beneath these abrupt contacts (Plates 1.1, 2.1 and 2.2). The upper member is up to 7.6 m thick in outcrop (DNP78-4), and 23 m in testholes (GSC69-4, Fig. 3.3).

Three lithofacies have been recognized within the upper member.

1. Unlayered diamicton (UD), occurs along the base of the upper member of formation B and forms about 80 percent of this member. It is well-exposed at Evilsmelling Bluff (DNP79-11, unit 8 and DNP79-14, unit 4, Plate 3.10), at the southeast end of Island Bluff (DNP78-4, unit 12), and in the centre of Golden Valley Bluff (DNP78-13, unit 9; and DNP81.6, unit 7, Plates 1.1 and 3.13).
2. Diamicton containing lenses (DCL) overlies lithofacies UD and occurs along about 20 percent of the outcrop. It is commonly less compact and more recessive (Plate 3.13) than other diamicton lithofacies. It is best exposed along the southeast end of Evilsmelling Bluff where it is up to 3 m thick (Plate 2.17 and 3.14).

a.



b.

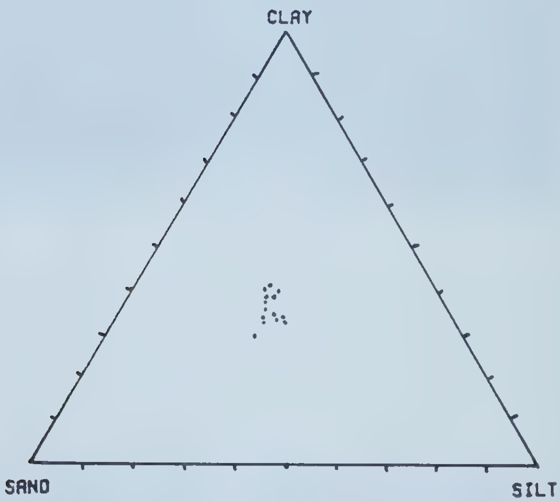


Figure 3.10. Grain-size distribution for diamicton in each lithofacies within the upper member of formation B.
a. all lithofacies b. lithofacies UD.

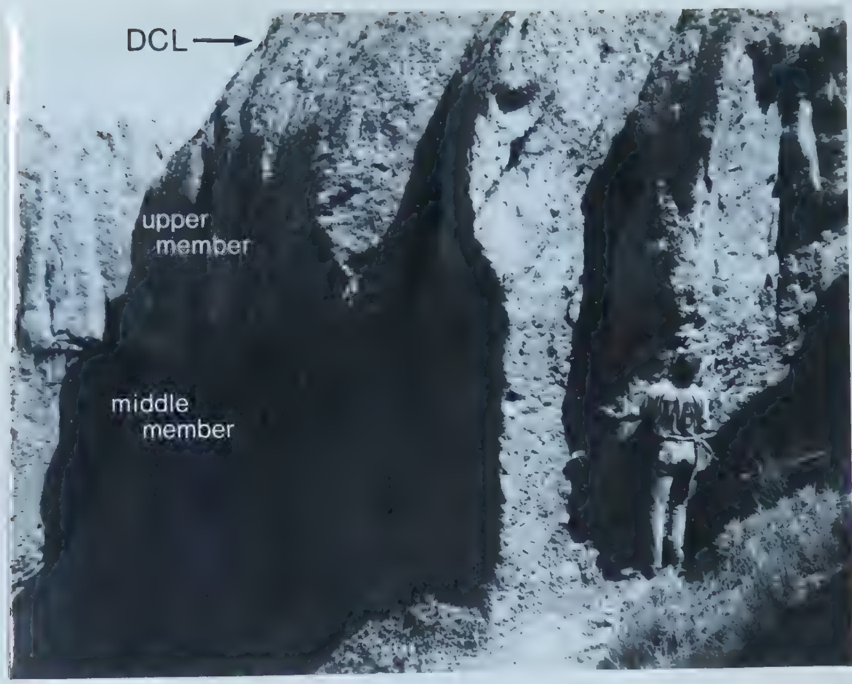


Plate 3.13. Unlayered diamicton (lithofacies UD) in the base of the upper member of formation B in the central part of Golden Valley Bluff. Note the sharp basal contact of lithofacies UD and the gradational contact with the overlying lithofacies DCL (diamicton containing lenses).

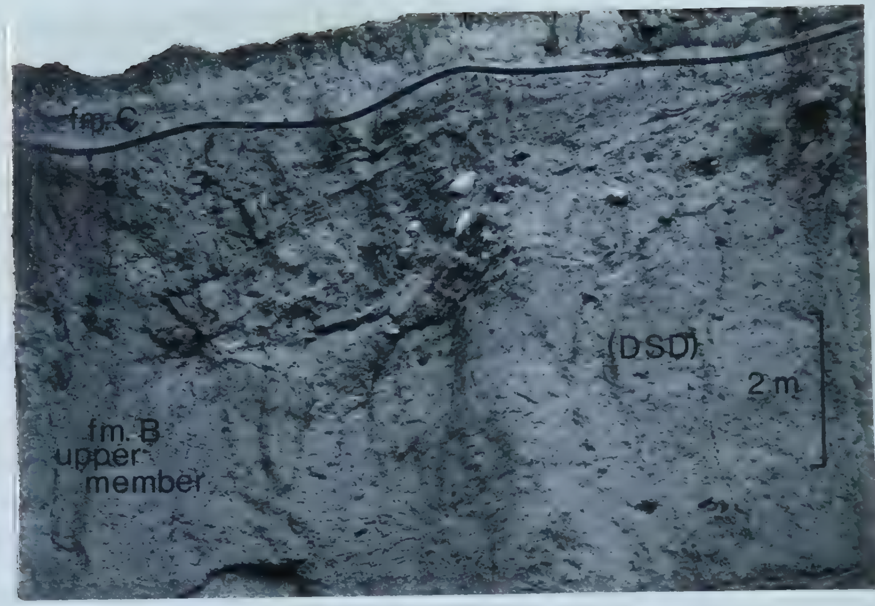


Plate 3.14. Diamicton containing lenses (lithofacies DCL, incorrectly labelled DSD) in the upper member of formation B at Evilsmelling Bluff. The gravelly zone in the centre of the photograph is within a collapsed sand and gravel lens.

3. Intermittent clast alignments (lithofacies ICA) consisting of large, flat-lying cobbles that are partially enveloped by the substrate, occur along the base of, and within the diamicton units of this member. They are best seen along Island Bluff.

The inclusion of these lithofacies within the upper member and the correlation between outcrops is based largely on its unique appearance. In particular, the large columnar jointing that commonly extends through the unit, its colour, and its sandy texture (Table 3.2, Fig. 3.4). Furthermore, contacts between lithofacies within the upper member are gradational, so that further subdivision is not possible.

F. Formation C

Formation C is the surface unit over most of the study area. It includes the modern sediment within the South Saskatchewan River valley. The mapping and correlation of the five lithofacies within this formation is not possible due to their discontinuous nature. They include the following:

1. A thin, discontinuous fining upwards sequence of parallel, interbedded light yellow silt and dark gray clay beds. Where clay beds occur, rhythmites are common. Basal contacts with formation B diamicton are commonly gradational. This lithofacies is up to 2 m thick and occurs as undeformed thin-bedded fill in small depressions in the top of the diamicton of formation B.
2. Cross-bedded fine to medium sand that occurs as fill in the bottom of some depressions on the top of formation B (Plate 3.15). Basal contacts are sharp and these deposits are up to 2.5 m thick.
3. A parallel bedded (10 to 30 cm thick), columnar jointed (3 by 3 cm by bed thickness), very fine sand and silt that commonly contains apparent paleosols (Plate 3.15). This lithofacies is up to 3 m thick, has a sharp basal contact and is found along the top of steep cliffs. It is generally more recessive than the underlying sediment. At one location on top of Bain Bluff near DNP78-10, it contains an ash identified on the basis of mineralogy by N. Catto (University of Alberta, personal communication, 1981) as Mazama tephra.
4. Interbedded diamicton, sand, silt, gravel and clay (lithofacies IDSS-L, Plate 2.21). Bedding is generally discontinuous, lenticular and less than 10 to 20 cm thick. Large clasts

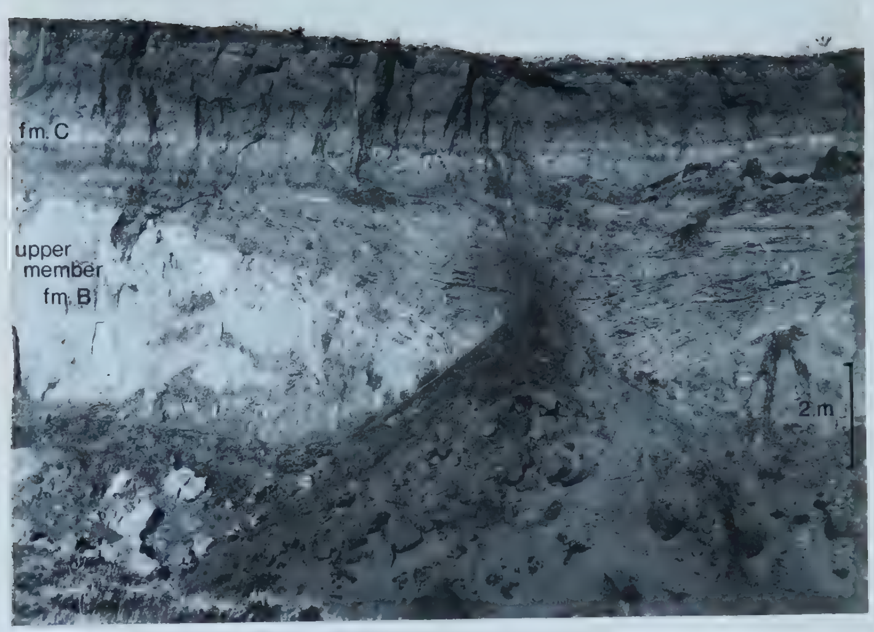


Plate 3.15. Cross-bedded sand of formation C infills a a depression on top of diamicton of the upper member of formation B at the west end of Island Bluff. It is overlain by bedded, columnar jointed very fine sand and silt that contains paleosols (dark grey). The white bands are calcium carbonate rich silt and sand beds.

of diamicton, silt, and clay are common. It is exposed as fills in gullys that have dissected most of the Pleistocene sequence particularly at the north end of Golden Valley Bluff (Plate 3.1), where it has the geomorphic form of an alluvial fan. There the sediment is up to 8 m thick and contains large mammal bones in several places. No detailed study of this lithofacies was undertaken.

5. Sand, gravel, and silt that form the modern alluvial plain of the South Saskatchewan River and its tributaries. This sediment was not examined in detail.

IV. LITHOFACIES INTERPRETATION

The following interpretation of lithofacies involves, among other things, a review of the processes that could have taken place in the formation of each. Modern analogs are referred to where possible and theoretical concepts utilized when necessary. The complete depositional environment in which the stratigraphic sequence of lithofacies was deposited is reconstructed in chapter V.

A. Terminology

Till is sediment that has been transported and deposited by or from glacier ice, with little or no sorting by water (after Dreimanis, 1982a).

Melting out is deposition of diamicton by the slow release of glacial debris from ice by melting and / or sublimation without sliding or deforming internally (after Dreimanis, 1982a).

Lodgement is deposition of diamicton from the sliding base of a dynamically active glacier by pressure melting (after Dreimanis, 1982a).

Rain out is deposition of sediment by falling through a column of water from floating ice.

Undermelting is used to refer to the detachment of a glacier from its bed by melting from the base up.

B. Unlayered diamicton (UD)

Lithofacies UD occurs as relatively thick (more than 1 m) deposits, in basal positions within associated sediment sequences and is interpreted to have been deposited subglacially. Basal melting out, lodgement, and / or basal molding of pre-existing sediment could have been involved in its formation. The lower part of formation A and the upper member of formation B (Table 3.1), where they contain unlayered diamicton, are interpreted in this manner.

In the following discussion, the processes for the deposition of lithofacies UD are outlined and the origin for its physical characteristics are discussed. All involve the glacial environment, but the first two, which occur subglacially, are most likely.

1. Melting out from the base of stationary ice.
2. Lodgement, melting out or molding of sediment along the base of actively flowing ice.

Other possible interpretations:

3. Letting down of supraglacial debris.

4. Raining out from a floating ice margin or pack ice.

5. Deposition from a single debris-flow.

1. Melting out from the base of stationary ice

Melting out has been observed at the base of some modern glaciers (Boulton, 1970a; Lawson, 1979b) where melting is attributed to a combination of geothermal heat, pressure melting, heat due to friction from flowing ice, heat provided by the presence of free water, and to water flow in or beneath basal ice (Boulton, 1970a). Melting occurs along the basal ice contact and may also occur within a basal zone (Lawson, 1979b).

Two major factors control the character of sediment that is deposited from a basal position in stationary ice:

a. The degree of confinement of meltwater by ice (Lawson, 1979b).

b. Basal debris concentration and the nature of its distribution (Boulton, 1970a; Lawson, 1979b, 1981b).

In the following discussion each of these factors is considered. The key characteristic within lithofacies UD is the lack of, or minimal occurrence of visible primary structure, in particular, the lack of sorted sediment.

a. The degree of confinement of meltwater by ice

The presence of flowing water is necesary to transport, sort, and ultimately deposit sorted sediment under a glacier. It is likely that any structures created subglacially by water would be preserved unless later disturbed by moving ice. Abundant water must have existed at the base of and within basally melting Pleistocene continental glaciers (Rothlisberger, 1972; Shreve, 1972; Weertman, 1972, Nye, 1976; 1982). However, it is the nature and rate of meltwater flow as it drains from the glacier that determines the nature of the sediment deposited. If there is sufficient water flow, sediment is washed and sorted. The likelihood of preserving some evidence of this sediment within diamicton is great, unless it is later remobilized -- a subject that is discussed below in the section on subglacial sediment molding.

Slow drainage of a glacier is probably associated with slow melting, because conduits within ice are produced primarily by rapidly escaping water (Rothlisberger, 1972; Shreve, 1972; Nye, 1976). Faster rates of melting in stationary ice lead to the presence of more free water and probably ultimately to the creation of good drainage due to the frictional heat supplied by the water flow (Nye, 1976). Therefore, if the deposition of lithofacies UD occurred from stationary ice, drainage must have been slow, with water flowing between ice crystals and along foliation planes in clean ice (Shreve, 1972) and intergranularly in debris-rich zones (Lawson, 1979b), so that little or no sediment sorting occurred.

b. Basal debris concentration and the nature of its distribution

The basal debris-rich zone of modern glaciers is either a structureless mixture of ice and sediment or, more commonly, it is stratified, with bands of debris-rich ice separated by clean ice bands (Boulton, 1970a; Shaw, 1977b; Gow, 1979 *et al.*; Herron and Langway, 1979; Lawson, 1979b; and others).

The basal conditions that are required to produce an unlayered diamicton by melting out from inactive debris-rich basal ice must account for microclast preferred orientations that have multiple peaks all within a single 50° to 120° azimuth range (Fig. 2.3; b, c, f, g, and j), indicating 25° to 60° scatter about an average direction (note that these measurements are two-dimensional and therefore do not indicate the direction of motion of the depositional agent). There are no microfabric data available from modern glacial studies for comparison with those that have been observed in lithofacies UD. However, Boulton (1971) has documented that elongate pebbles are oriented parallel and transverse to glacial flow direction, so that unimodal and bimodal clast orientations are produced. The presence of a broad unimodal or bimodal distribution of peaks within a microfabric could be the microclast equivalent of the much narrower distribution of pebble orientations. If this assumption is correct, then deposition could have occurred by slow melting out, with little grain movement.

Summary of deposition by melting out from the base of stationary ice

There are four basal melt-out possibilities to be considered.

a. Slow melting out and corresponding slow drainage of meltwater from debris-rich unstratified ice could deposit unlayered diamicton with unimodal or bimodal peak clusters of oriented microclasts inherited from the basal debris zone of a glacier (e.g. Fig. 2.3: a, b, f, g, j, k). In this case, ice within debris bands was likely interstitial.

b. Slow melting out and corresponding slow meltwater drainage from debris-poor unstratified ice, could deposit unlayered diamicton similar to that produced in (a). However, it is possible that a larger volume of void space would occur where debris contents are low, because there is more ice to melt. This could result in poorer preservation of microclast orientation (Fig. 2.3: d, e, h, i) because of grain migration by collapsing, flowing and squeezing into voids (Lawson, 1979b).

c. Slow melting out and corresponding slow meltwater drainage from stratified debris-rich basal ice would produce a stratified diamicton where debris bands differ in composition (Lawson, 1979b; discussed below for lithofacies SD) or where winnowing occurs along the ice-substrate interface..

d. Slow melting out and corresponding slow meltwater drainage from stratified debris-poor basal ice would disrupt microclast preferred orientation in the same way as for (b) above, probably with some preservation of stratification.

In summary, unlayered diamicton (UD) could have been deposited by slow basal melting with correspondingly slow drainage from stranded subglacial ice blocks or dead-ice masses to produce the following:

a. A deposit with a unimodal or bimodal distribution of microclast orientation peaks that formed from debris-rich ice.

b. A deposit with no microclast preferred orientation, that formed from debris-poor ice. Poor drainage was probably necessary to prevent sediment sorting.

2. Lodgement and melting out from the base of actively flowing ice

The origin of unlayered diamicton has traditionally been associated with the process of lodgement at the base of a flowing glacier (Flint, 1971). In the following section, the more widely accepted concepts of, and evidence for the processes of lodgement and molding beneath active ice are discussed. This background is then applied to the problem of the origin of unlayered diamicton.

Two major processes are considered in the following discussion:

a. Frictional lodgement from the base of actively flowing ice

Deposition by lodgement "occurs when the frictional drag between clasts in traction and the bed over which they move is such that the force imposed on them by moving ice is insufficient to maintain them in motion" (Boulton, 1975: 20). The process of clast lodgement and the development of associated glacigenic flute casts, grooves, and striations has been observed at the base of actively moving ice in the modern glacial environment (Boulton, 1976; Kruger, 1979). However, the lodgement of particles finer than small pebbles has not been documented because of the difficulties in observing them.

Evidence for the lodgement process can be inferred from flutes, grooves and striations along sharp basal contacts that are overlain by till, even where lodged pebbles or cobbles are absent (Boulton, 1970a; Kruger, 1979). These glacier tool markings are likely to occur as consistently oriented lineations along the same stratigraphic position for distances of a few centimetres to tens of metres. The length of grooves exceeds the dimensions of the pebbles or cobbles that made them by many times; therefore, the probability of observing grooves or flute casts is much greater than of finding lodged pebbles or cobbles, especially where stone contents are low, as in the study area.

More indirect evidence of the lodgement process lies in the existence of drag folds (recumbent isoclinal folds) within sediment that underlies the sharp basal contact of a till lithofacies. Glacier movement along its bed causes deformation of the substrate by frictional drag (Berthelsen, 1979; Boulton, 1979).

The deposition of the sand- to clay-sized fraction of diamicton can also occur by the process of lodgement. This occurs by a combination of frictional drag and pressure

melting along the base of a glacier (Boulton, 1975; Lawson, 1981b) and can result in the subglacial accretion of an unlayered diamicton (Kruger, 1979).

Pebble and microclast preferred orientations for lodgement till commonly exhibit unimodal or bimodal distributions with narrow peaks (Boulton, 1971; Kruger, 1979). This is a function of the complete domination of this subglacial environment by sliding ice, which destroys water-sorted sediment structures so that they are not preserved. Clast alignments are predominantly parallel and perpendicular to ice flow direction.

b. *Melting out from the base of actively flowing ice*

Hallet (1979a) concluded from theoretical considerations that particles on a debris-poor glacier sole will remain in motion unless sliding velocity is reduced to about the basal melting rate. This could allow for the formation of sharp erosional basal contacts during normal glacial flow due to basal abrasion and subsequent deposition of fines by melting out when basal ice flow velocities decreased. If Hallet's ideas are applied to the subglacial deposition of unlayered diamicton, then a reduction in ice flow velocity to allow release of debris could provide suitable conditions for the accretion of lithofacies UD. No sediment sorting would occur if drainage rates were sufficiently slow. Therefore, microclasts could exhibit unimodal or bimodal preferred orientations inherited from flowing ice (Hallet, 1979a).

c. *Subglacial molding by actively flowing ice*

Subglacial molding refers to the process of plastic deformation by shear that occurs as ice flows over a deformable substrate (Boulton, 1970a, 1979). The evidence used to support the lodgement process above can also be interpreted to be the result of subglacial molding of a predominantly diamicton substrate. There are two possibilities.
(i) Continuous molding of sediment or a sediment slurry as it melts out of the base of a glacier would prevent the preservation of any structure and would preferentially orient clasts parallel and perpendicular to ice flow (Boulton, 1975).
(ii) Ice drag along a pre-existing substrate could produce lithofacies UD. Near the surface of this substrate, in a zone that would roughly coincide with the thickness of a given

unlayered diamicton bed, deformation could be strong enough to completely obliterate pre-existing structures, including sorted sediment features. The material left behind by this process could be a structureless diamicton (lithofacies UD).

Therefore, sediment that existed prior to an advance or that melted out of stationary ice during an advance could be reworked by this process to produce lithofacies UD. The preferred orientation of pebbles and microclasts would resemble that of lodgement till, because of clast reorientation during subglacial molding (MacClintock and Dreimanis, 1964). Deformation structures such as fractures and smears, formed by lodgement or subglacial molding might also be preserved in diamicton. However, the lack of more detailed data from the modern environment make it hard to distinguish between lodgement and subglacially molded deposits. Therefore, they are not differentiated in the following interpretation of sediment in the study area.

Genetic interpretation of lithofacies UD in the stratigraphic sequence

There are two occurrences of lithofacies UD within the stratigraphic record at Medicine Hat. Each can be interpreted to be the result of a combination of one or more of lodgement, melting out or subglacial molding from active ice.

1. Base of formation A

The following observations were made at the base of lithofacies UD at DNP80-52 and DNP81-8 (Fig. 2.2), along the north end of Golden Valley Bluff (Plate 3.1):

a. Probable drag folds along the sharp basal contact of unlayered diamicton (formation A) are preserved along the surface of the underlying rhythmically bedded silt and clay (Plate 4.1) at the east end of Island Bluff and at the north end of Golden Valley Bluff (Plate 2.3). The orientation of drag-fold axes is clustered around an azimuth of 50° (Fig. 4.1).
b. Scratches measured in the same horizon (Fig. 3.8) have about a 115° orientation and another of about an azimuth of 25° (Fig. 4.2: d). The 25° orientation is about perpendicular to the valley wall where it has been measured. The presence of rotational slides along the valley walls in this area indicate that a mass movement origin for this orientation of scratches is likely.

Plate 4.1. Small-scale drag-folds in a sandy lithofacies of the middle member of the Empress Formation at the east end of Island Bluff. Photograph taken about 1 m below the sharp basal contact of unlayered diamicton of formation A.

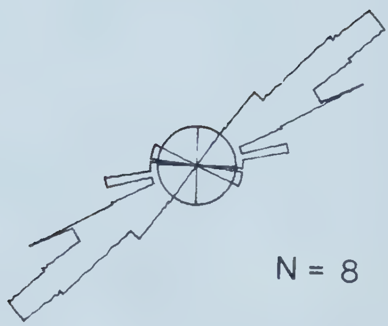


Figure 4.1. Rose diagram (20 degree moving average) showing the orientation of drag-fold axes measured in the sandy middle or upper member of the Empress Formation, directly below the base of formation A at Island Bluff.

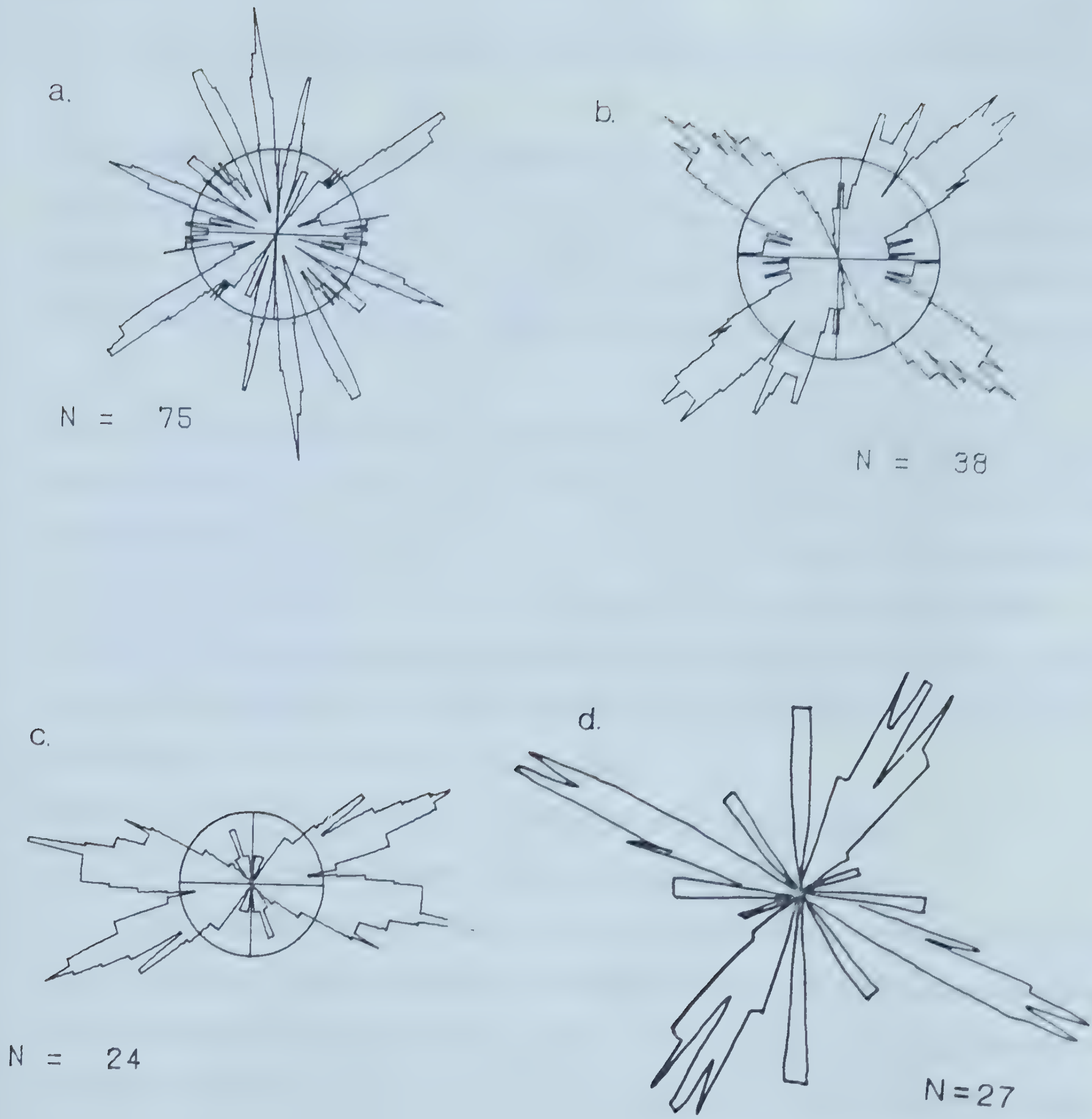


Figure 4.2. Rose diagrams (10 degree moving average).
a. to c. The variation in microclast orientations for three zones within a single sample of lithofacies UD (unlayered diamicton) shown in Plate 4.2.
d. The orientation of scratches measured in the fracture zone along the base of unlayered diamicton at the same locality as the sample was taken.

c. Horizontal fractures (Plate 2.4) and fracture zones (Plate 2.5) occur in this basal contact zone.

d. Smudges of silty clay are present within the basal portion of lithofacies UD.

If it is assumed that scratches oriented at about 30° are caused by mass movement, the drag folds and 120° scratches could have been caused by glacial overriding (Berthelsen, 1979; Boulton, 1979) along the 115° to 295° direction. They are interpreted to have been created subglacially during lodgement and/or molding (Boulton, 1970a; Kruger, 1979).

Microfabric measurements (Fig. 4.2) taken from three texturally different zones on a thin section (Plate 4.2) of unlayered diamicton (DNP81-8, formation A, north end of Golden Valley Bluff) from a few centimetres above its sharp erosional base exhibit different orientations. It should be noted that the diamicton at this sample location contains drawn-out bands of clayey material (less than 0.5 by 3 cm in size). Only three zones in this thin section contained enough grains for analysis. These are shown in Figure 4.2 (a-c).
Zone 1 (Fig. 4.2: a) has no preferred orientation.
Zone 3 (Fig. 4.2: b) has a polymodal distribution of orientation peaks.
Zone 7 (Fig. 4.2: c) has two peaks that are within 30° of each other.

This difference in the nature of grain orientation between zones in a single sample can be explained by their probable different origin. Zones 1 to 4 are unlayered (Plate 4.2) and could be basal melt-out sediment. The lack of preferred orientation in these zones suggests that grain movement occurred during melting out, destroying any existing preferred orientation. Zones 5 to 7 contain microstructures that could be part of a shear zone. The relatively small separation between the two narrow peaks in zone 7 (67° and 95°; Fig. 4.2, c) suggests that they were affected by flow, possibly in a shear zone.

The orientation of scratches found along the basal contact fracture zone of lithofacies UD at this location are shown in Figure 4.2 (d). Note the similarity between the orientation of peaks in this diagram and that of Figure 4.2 (b). As mentioned previously, the scratches oriented about an azimuth of 25° to 30° - 205° to 210° are interpreted to be post glacial -- possibly recent -- caused by mass movement of the valley wall. It is possible that these microclast orientations (30°-210° and 135°-315°) and scratch orientations

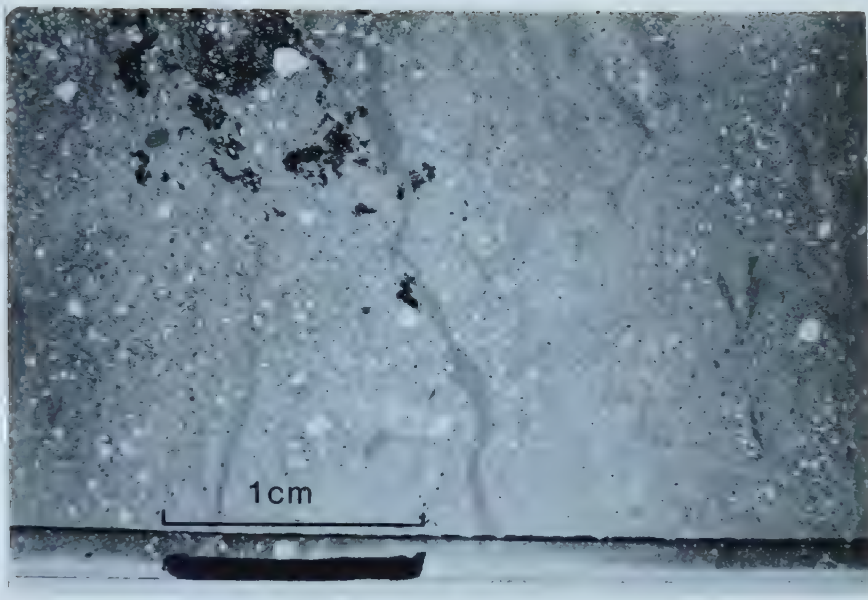


Plate 4.2. Photomicrograph of a sample of lithofacies UD (unlayered diamicton) at DNP8.1-8. The dark gray structures in the right half of the photograph may be micro-shear structures.

(115°-295°) were formed by shear in the same direction. The two major microclast peak orientations may have formed transverse (30° to 120°; coincidentally parallel to the direction of mass movement into the valley) and parallel (135° to 315°) to ice flow direction. Similar parallel and transverse pebble orientations have been noted by Boulton (1971), as they formed in the till of Svalbard glaciers. The scratches (115°-295°) likely formed parallel to ice movement.

If this interpretation of the orientation data is valid, then it is likely that lithofacies UD, in the above stratigraphic position (base of formation A), was formed by subglacial molding in an environment that also formed drag folds. The slightly different, nearly unimodal orientation of microclasts exhibited in zone 7 of the same thin section (67° and 95°; Fig. 4.2 c) could have formed when the ice flowed in a slightly different direction. This type of local variation in basal ice flow direction has been observed by Boulton (1971). A comparison of the texture of lithofacies UD within formation A along its base at the north end of Golden Valley Bluff with other samples of lithofacies UD from the same unit indicate that the basal zone contains less sand and more clay (Fig. 4.3), which is predictable given the occurrence of smeared clay bands. This further supports deposition or molding in a subglacial position with some incorporation of the underlying silty clay substrate. It is also possible that deposition and lodgement alternated to form this sequence.

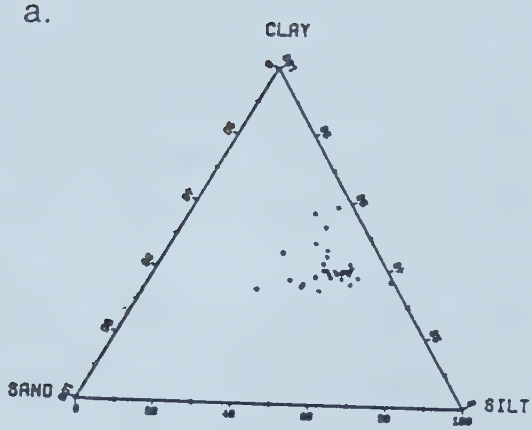
2. Base of the upper member of formation B

The other occurrence of lithofacies UD is in the basal part of the upper member of formation B. The following observations are used to support a subglacial melting out and/or molding genesis.

a. The basal contact of lithofacies UD is sharp and planar (Plate 3.10), from which it is inferred that shear occurred along this horizon.

b. Deformation directly below lithofacies UD includes both folding and overthrusting similar to glaciotectonic structures reported by Banham (1977), Berthelsen (1979), and Boulton (1979) (Plate 2.1, at Golden Valley Bluff). Farther north along Golden Valley Bluff, *en echelon* silt bed segments, at the same stratigraphic level are also interpreted to have

a.



b.

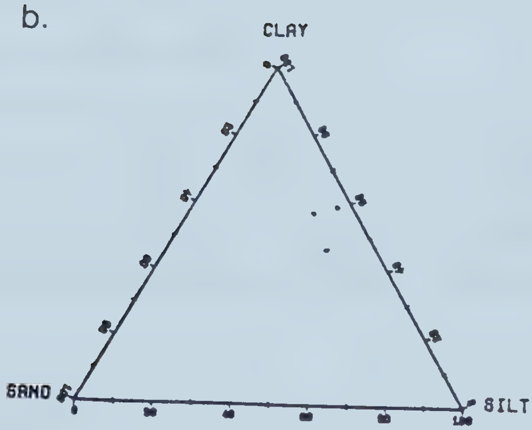


Figure 4.3. Ternary diagrams showing the grain-size distribution of diamicton for:
a. all lithofacies within formation A, and
b. samples from within 30 cm of the base of lithofacies UD (unlayered diamicton).

been glacigenically formed. This provides further evidence that shear occurred at this stratigraphic level.

c. Microfabric and pebble fabric data from lithofacies UD in this stratigraphic position show peak clusters in the southwest - northeast to east - west quadrants, with no significant peaks transverse to them (Fig. 4.4). This relatively consistent microfabric is difficult to form and preserve without consistently directed local flow.

All of these characteristics could have been formed subglacially by some combination of basal melting out, lodgement, and molding. The sharp basal contact of lithofacies UD in this position and the underlying deformation were likely created by subglacial erosion and drag.

Subsequently, deposition of lithofacies UD probably occurred by melting out due to regional pressure melting or thawed bed conditions (Boulton, 1975; Hallet, 1979b; Lawson, 1979b, 1981b). Ice flow could have continued over the bed with a gradual accumulation of sediment on top of the substrate by these mechanisms (Boulton, 1971). However, continued molding of diamicton by the overriding glacier base would have destroyed any small-scale sorted sediment structures and could also have created, strengthened, or changed the preferred orientation of microclasts (MaClintock and Dreimanis, 1964; Boulton, 1970a, 1971; Lawson, 1979b) so that they became aligned parallel to the more recent ice flow direction.

There is no way to differentiate between a primary depositional fabric and an early postdepostional one. However, unlayered diamicton with the relatively consistent microclast orientation found in lithofacies UD at the base of the upper member of formation B could have been deposited and preserved as a single unit at the base of a glacier.

Alternative interpretations

1. Letdown of supraglacial debris

Deposition of unlayered diamicton from a supraglacial transport position is not considered, because of the lack of supraglacial debris carried by a continental glacier on the plains. However, as the upper surface of a receding glacier melts, a relatively high local relief ice surface commonly develops and debris that is carried

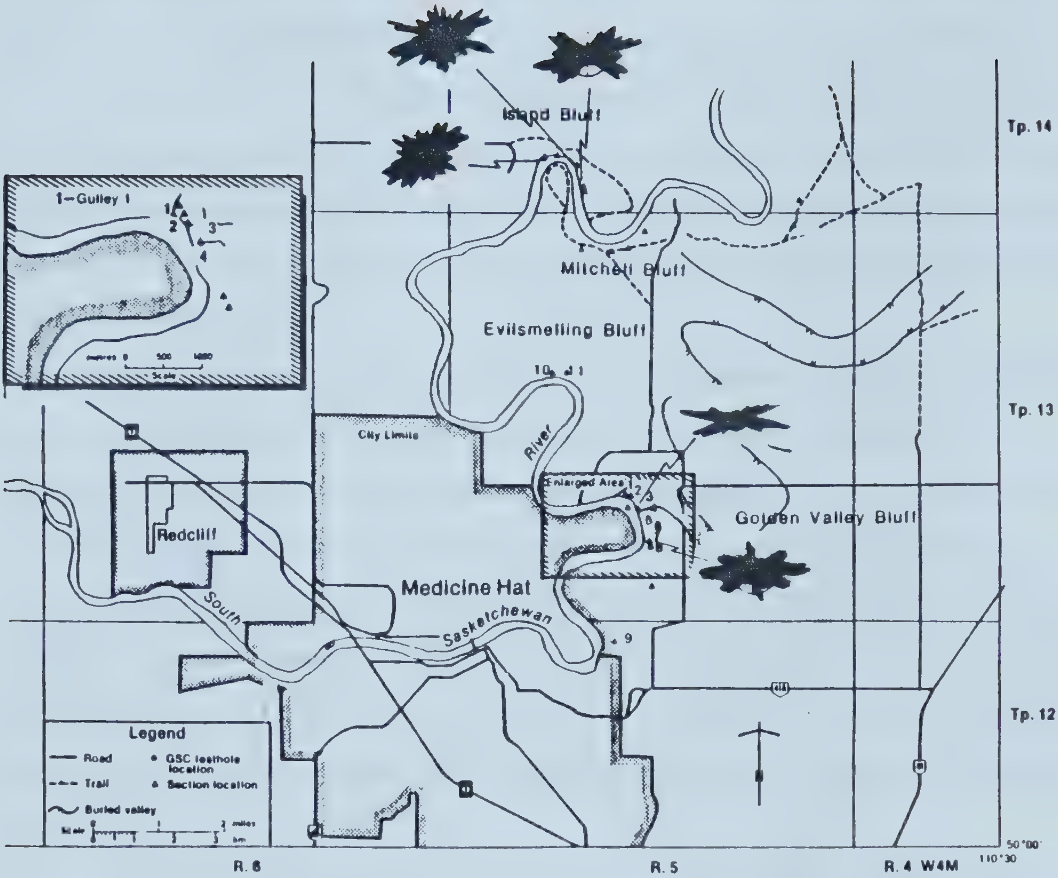


Figure 4.4. Microclast preferred orientations from lithofacies UD (unlayered diamicton) in the upper member of formation B show a broad east-west to northeast-southwest trend.

high in the basal debris zone accumulates on the surface (Boulton, 1971; N. Eyles, 1979). In places, this debris layer is sufficiently thick, about equal in thickness to the active layer, to insulate the underlying ice (N. Eyles, 1979; Shaw, 1979). However, collapse and slumping due to melting of ice slopes too steep to hold sediment maintains a dynamic environment in which resedimentation occurs frequently. Eventually, as the ice completely melts away, resedimented debris is let down onto the substrate (Boulton, 1971; N. Eyles, 1979; Lawson, 1982). The resulting deposit may contain many lenses and laminations of sorted sediment and lack a preferred orientation of clasts (N. Eyles, 1979). This process is therefore not likely to produce unlayered diamicton.

However, where surface melting is inhibited by debris cover so that melting occurs primarily along the base of the glacier, a high-relief surface might not develop and deposition of a diamicton that lacks evidence of water sorting could occur. It is deposited where debris is let down from a supraglacial position -- attained by the release of debris by melting out along the upper surface of the basal debris-rich zone -- onto the substrate (Boulton, 1970a, 1971, 1972b). However, the potential for differential melting and small-scale sediment movement are high in this environment, so that a preferred orientation of microclasts inherited from ice flow is unlikely.

Within this study, lithofacies UD occurs directly overlying units that have characteristics interpreted to have been caused by glacial overriding, such as a sharp erosional basal contact with drag-folds and shear fractures along it. Diamicton in this position is interpreted to have been deposited subglacially.

2. Rain out from a floating or undermelted ice margin or pack ice

The last glacial advance into the Medicine Hat area came from the north, northeast and northwest, as documented by Westgate (1968), Berg and McPherson, (1972), and Shetsen (1984; Fig. 1.1, chapter I). It probably dammed northeastward flowing rivers resulting in a lake basin that filled and expanded until outlets were reached to the south. Using the present elevation of this terrain, it is estimated that more than 100 m of water could have accumulated in a lake basin that included the Medicine Hat area. This depth should be considered as a minimum, because isostatic

depression in front of the ice could have deepened the basin. However, no data are available to estimate the amount of downwarping. It should be noted that similar lakes probably formed in front of earlier continental glacier advances into the area (Stalker, 1976a) for the same reasons.

Thick, laterally continuous unlayered diamicton deposits can be produced by rain out from floating ice that contains debris (Kurtz and Anderson, 1979; Anderson, 1983). However, the following observations within or in association with lithofacies UD are not consistent with characteristics of rain out deposits.

a. The sharp basal contact, commonly with associated underlying drag folds and scratches.

b. The absence of dropstones.

c. The preferred orientation of microclasts.

3. Deposition from a single debris-flow

The use of the term debris-flow follows that of Carter (1975) and Enos (1977). It is a viscous mass flow with an appreciable content of suspended clasts. Large subaerial and subaquatic debris-flows can deposit thick, unlayered diamicton from their plug zone (Middleton and Hampton, 1976; Lawson, 1982; Lowe, 1982; Domack, 1983). However, they also commonly deposit a basal zone that has some evidence of lamination, sorting, or grading due to shear. Where deposited subaquatically, debris-flows may also produce similar sorting, grading or lamination above the unlayered plug in response to shear at the water-sediment interface (Hampton, 1972; Lowe, 1982).

The unlayered diamicton of lithofacies UD does not have these laminations. Furthermore, there is no evidence of soft sediment deformation along the basal contact of lithofacies UD, a structure that is common in rapidly deposited sediment such as flow deposits (N. Eyles, 1983). In addition, lithofacies UD that occurs in the upper member of formation B, has a continuous lateral extent of more than 1.5 km (Plate 1.1, Golden Valley Bluff), and is likely more than tens of square kilometres in areal extent. It also has a relatively consistent microfabric preferred orientation as shown on Figure 4.4. This would require a consistent flow direction over a large area to form.

The generation of a single flow that would be capable of depositing unlayered diamicton of this magnitude requires more relief than the present prairie surface provides. Nonetheless, a sediment source located on the surface of a glacier could provide the necessary relief. The release of such a large volume of material in a single flow event would probably be a rare event, requiring a tremendous surface accumulation of sediment and subsequent simultaneous release of the entire mass. Large subaerial proglacial flows on the order of 0.5 km have been observed in the modern glacial environment of Vestspitzbergen by Boulton (1968), so that the scale is conceivable. However, lamination, sorting and grading are present in these recent deposits. In addition, the relatively large-scale deformation below the basal contact of lithofacies UD in this stratigraphic position probably could not have been caused by a debris-flow. Therefore, it is unlikely that lithofacies UD could be deposited by a single large debris-flow.

Summary

In summary, basal melting out, lodgement, basal molding, letdown of supraglacial debris, rain out from a floating or undermelted ice margin or pack ice, and deposition from a single large debris-flow have been explored as possible origins for lithofacies UD, unlayered diamicton. It is concluded that the most likely depositional processes for lithofacies UD are as follows:

1. Melting out from the base of a stationary glacier.
2. Subglacial lodgement.
3. Molding of relatively unconsolidated sediment by an overriding glacier.

Unfortunately, there is insufficient data available to distinguish between these types of deposits. However, it is apparent that lithofacies UD formed subglacially.

C. Stratified Diamicton (SD)

Three possible origins can be inferred from the even, parallel nature of the beds and laminations within the sediment that occurs in lithofacies SD. They are as follows:

1. Deposition from multiple subaquatic debris-flows (considered to be the most likely).
2. Rain out from a floating or undermelted debris-rich ice margin or pack ice.

3. Basal melting out from a glacier.

1. Deposition from multiple subaquatic debris-flows

The lamination and bedding within lithofacies SD suggests that it was deposited in water. Where laminae occur, textural gradation within beds was likely caused by settlement from suspension or by the upward escape of water from rapidly depositing sediment. These characteristics could develop subaerially or subaquatically.

The following observations provide evidence for the deposition of lithofacies SD by multiple subaquatic debris-flows.

1. The relative lack of large pebbles and cobbles compared with other diamicton in the area (Anderson, 1983).
2. The sharp upper and lower contacts of most beds (Anderson, 1983).
3. The consistent thickness of bedding over tens of metres.
4. The presence of pebble-sized, soft sedimentary clasts (Enos, 1977; Anderson, 1983).
5. The absence of shear planes or fractures (DeJong and Rappol, 1983).
6. The high variability in microclast preferred orientation (Fig. 2.4) as discussed by DeJong and Rappol (1983).

It is important to note that a subaerial environment is unlikely for the deposition of lithofacies SD for the following reasons.

1. Larger clasts that have dimensions exceeding the thickness of bedding (Plate 2.14) could not have been carried by the thin flows that are interpreted to have deposited the finer sediment (Naylor, 1980; Anderson, 1983). Deformation under these larger clasts (Plate 2.14 and Fig. 2.5) suggests that they are dropstones (Anderson, 1983). Some of these larger clasts are oriented with their long axis vertical, further supporting a dropstone origin (Gibbard, 1980).
2. The lack of erosion or channelling on top of beds favours a subaquatic environment.
3. The horizontal contacts and apparent broad lateral extent of beds in lithofacies SD are more likely to form subaquatically (Anderson, 1983).

These sorted interbeds could be the result of winnowing and sediment transport by underflow currents on top of debris-flow deposits (Boulton, 1972b; Evenson *et al.*,

1977; Gibbard, 1980). The absence of significant silt and especially clay beds or laminae in subfacies SD-L is probably due to turbulence. In modern proglacial lakes, continuous density underflow, especially in glacial proximal areas, is interpreted to be generated by the constant influx of meltwater (Theakestone, 1976), which prevents most of the suspended fines from settling out near the sediment source. This might also occur in large subglacial, water-filled cavities (discussed below).

Alternatively, evidence from laboratory experiments (Hampton, 1972, Lowe, 1982) indicates that a sequence similar to lithofacies SD (Fig. 2.5) can be deposited by subaquatic debris-flows. Individual diamicton beds are deposited by the main body of a debris-flow. Shear along the top of each flow caused by friction with overlying water may also contribute some of the sorted sediment that forms the laminations present in lithofacies SD-L (Middleton and Hampton, 1976; Naylor, 1980). In addition, upward fluid escape as a debris-flow stops may contribute some sorted sediment (Naylor, 1980).

The faint lamination present in some diamicton beds (Plate 2.14) may represent a composite of deposits from different flow types that were initiated during the same flow event. In particular, the thin sandy beds up to 0.5 cm thick (Fig. 2.5) could have been deposited from small turbidity currents that separated out from the main debris-flow (Middleton, 1967; Hampton, 1972; Middleton and Hampton, 1976).

The pebble and smaller sized clasts of soft sediment observed within subfacies SD-L (DNP79-11 and 79-14) were likely ripped up by or slumped into these small flows and then abraded during transport before final deposition as rounded clasts (Evenson *et al.*, 1977; Anderson, 1983). In addition, lithified clasts in the same size range were rafted along by these flows, either on top of, or within the plug zone (Rodine and Johnson, 1976; Enos, 1977; Lowe, 1982). The absence of "gully-like erosive, lower bed limits" that are suggested by Dejong and Rappol (1983: 69) to be characteristic of debris-flow deposits may be the result of high density debris-flows that lacked erosive power (Middleton and Hampton, 1973; Enos, 1977).

The distinction between dropstones and other clast-related structures (mainly pebbles) is useful in reconstructing genetic processes. A dropstone is a pebble- to boulder-sized clast that occurs in a sequence that is interpreted to be waterlain. It is deposited by free fall from a floating source -- ice or organic material. Where water flow

or debris-flow has contributed to the deposit in which dropstones occur, the dropstones are larger than could have been carried by the corresponding water or debris-flow.

Criteria for the recognition of dropstones

1. Dropstones deform underlying stratification.
2. Dropstones are draped by overlying sediment.
3. Dropstones may lie flat on bedding planes, or be nearly vertical as a result of penetration of bottom sediment which supports them in this position.
4. Dropstones may penetrate sediment stratification. This occurs where bottom sediment is sufficiently saturated to have minimal strength. A deposit that shows this type of penetration would likely have wisps of material similar in composition to the stratification trailing upwards from dropstones.

However, the distinction between subaquatic and subglacial structures that are similar to those asssociated with dropstones is more difficult. For example, a pebble- to boulder-sized clast that is pushed into the substrate by stationary ice as it melts, would deform underlying stratification, resulting in a structure similar to the deformation beneath a dropstone. In the following discussion of debris-flow and till deposition, these structures are compared.

In the debris-flow mechanism, clasts that cut laminations (Fig. 2.5, clast 1) likely protrude above the upper zone of shear of the flow that rafts them, or above the traction carpet zone of subsequent turbidity currents or underflows and are therefore encircled by the sediment but not covered. Where the height of a clast sitting on top of the bed is exceeded by the thickness of a debris-flow, the clast is covered, but not draped (e.g. Fig. 2.5, clast 3). That is, the upper surface of the flow remains flat (Carter, 1975). Where a flow passes over a clast but is not thick enough to cover it after the flow stops, it is likely that the clast would shed its cover and protrude above the surface of the deposit. Most elongate clasts lie horizontally, (Fig. 2.5, clast 3) a position which is typical of debris-flow-rafted clasts.

The apparent symmetrical draping of clasts by overlying diamicton and laminae observed in subfacies SD-L (Plate 2.14) could be caused by early postdepositional

differential compaction. The soft cover sediment probably deforms around incompressible clasts and may also distort beneath them as water is expelled.

Where laminations are absent, stratified diamicton could have been deposited in the same way as subfacies SD-L sediment, by larger debris-flows, with proportionately larger volumes of associated sorted sediment derived from the basal and upper shear zones of the flow. This genetic association is reasonable because laminated (SD-L) and unlaminated stratified diamicton commonly occur in close physical association (e.g. DNP79-11). The lateral extent of individual diamicton beds, estimated to be up to hundreds of metres, is a reasonable scale for this type of deposit (Anderson, 1983). The probable existence of a proglacial ice-dammed lake, which could have been the depositional environment for lithofacies SD (Fig. 4.5), was established previously.

It is also possible that the deposition of lithofacies SD by debris flows may have occurred subglacially in one or more partially or completely water-filled cavities (Fig. 4.6 b and c). This could occur where a depression existed under the ice, such as a river valley, which would allow the ice to be supported by confined water within it. This subglacial ponding is theoretically possible, even for the observed 1.5 km lateral extent of lithofacies SD at Golden Valley Bluff (Rothlisberger, 1972; Nye, 1976). The volume of water measured during jokulhaups from modern glaciers (e.g. Grimsvotn, Vatnajokull, Iceland; Nye, 1976) indicates that subglacial and/or englacial water-filled cavities of this magnitude do occur. The height of the cavity could range from a few centimetres to tens or hundreds of metres. In this subglacial environment, sediment would be derived from mud that is squeezed into the cavity from beneath the glacier where it is in contact with its bed, and by gravity from the roof of the cavity (Boulton, 1970a).

Thus, there are modern analogs to suggest that this subglacial environment could exist. However, the preservation of lithofacies SD with little or no deformation requires that no subglacial deformation occurred subsequent to deposition. This could have happened if the ice stopped flowing, or if high pore water pressures were maintained to reduce effective stress after the cavity closed or filled with sediment. It is possible that lithofacies LD, which includes most of the middle member at Golden Valley Bluff, is the glacially deformed equivalent of lithofacies SD that crops out at Evilsmelling Bluff.

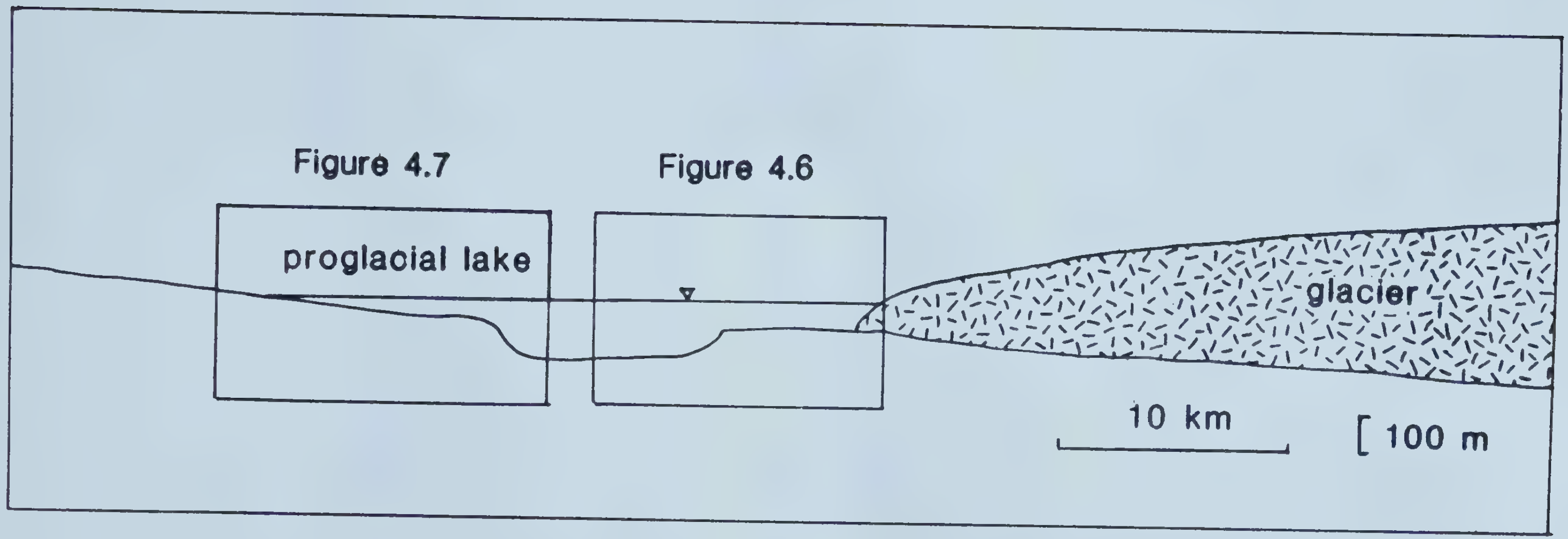


Figure 4.5. A regional view of a prairie glacier toe and proglacial lake showing the location of the schematic diagrams on Figures 4.6 and 4.7.

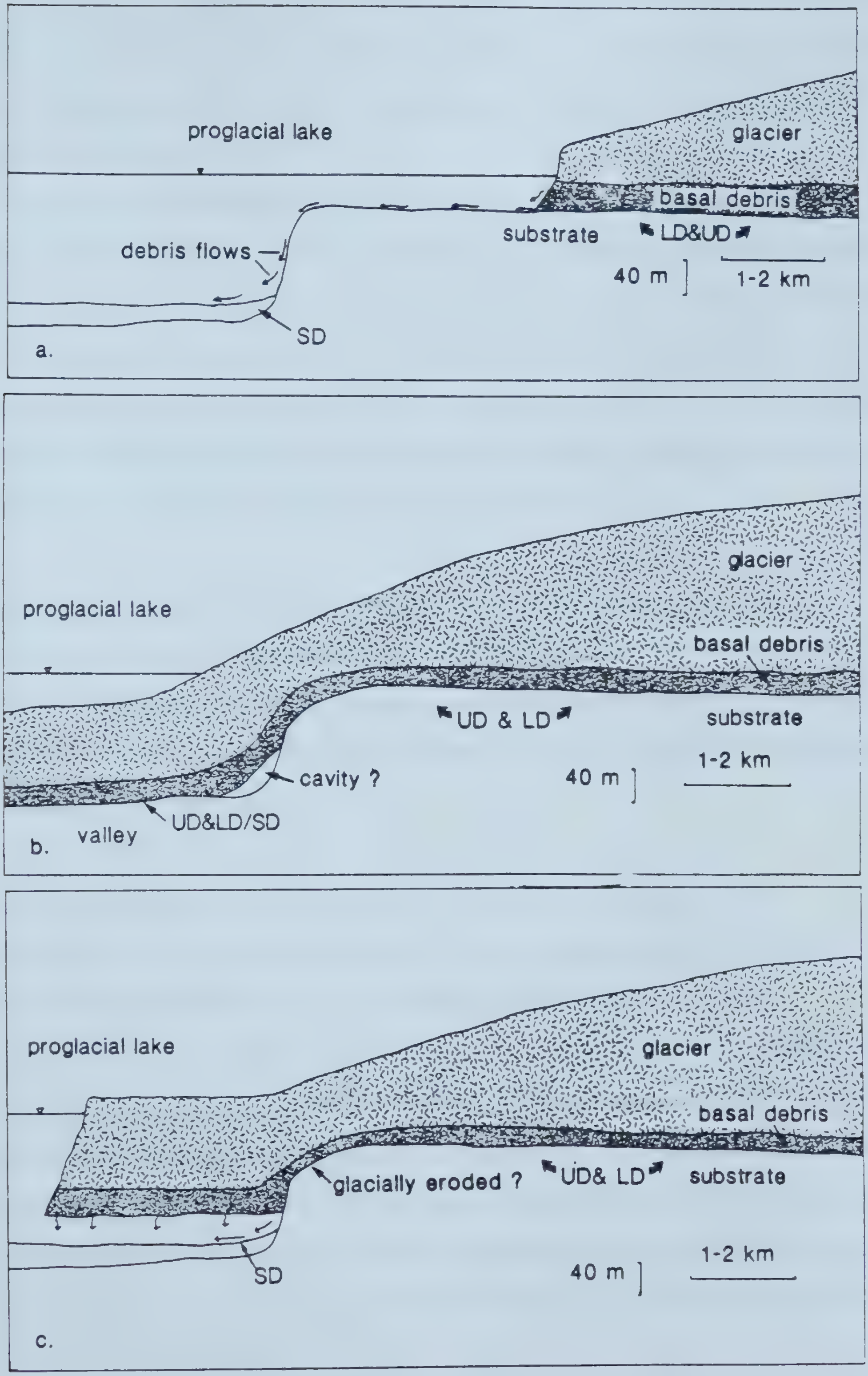


Figure 4.6. Schematic diagram showing the deposition of lithofacies SD (stratified diamicton) :
a. deposition by subaquatic debris flows. b. glacial margin infills a valley. Note the lee -side cavity. c. subsequent floating of the glacier margin and deposition of SD by rain out.

The microfabric data for one 70-cm sequence of subfacies SD-L sediments were presented in Figure 2.4 (a to d). None of the samples have a distinct preferred orientation. However, unoriented clasts are typical of sediment derived from the plug zone in many debris-flow deposits (Enos, 1977).

In summary, lithofacies SD could have been deposited by subaquatic debris-flows with some surface winnowing to sort sediment or the sorted sediment stratification may have been deposited from the basal and surface shear zones of debris-flows and from density undercurrents. Emplacement of dropstones from floating ice and subsequent differential compaction could account for all of the relationships between large clasts and stratification. The environment of deposition was likely a proglacial lake, although a subglacial cavity (or cavities) was also possible.

2. Rain out from a floating or undermelted ice margin or pack ice

A rain-out origin for lithofacies SD requires the presence of a proglacial lake formed by ice-damming of regional drainage. As mentioned previously, a proglacial lake was most likely present. The rain-out mechanism could account for the total deposit or contribute to a certain component.

The following characteristics support a rain-out origin for lithofacies SD:

a. The presence of dropstones (discussed for multiple subaquatic debris-flows).

b. The presence of lamination or bedding within the diamicton.

Grain orientations measured in the horizontal plane for rain-out sediment should show no preferred direction (Anderson, 1983). Figure 2.4 shows the results of several microfabric measurements for lithofacies SD in which this is the case, but the existence of undraped clasts within the thin stratification of lithofacies SD -- in many places thinner than the diameter of pebbles within it -- likely precludes a pure rain-out mechanism. However, rain-out could have provided sediment, which was subsequently redeposited by debris-flows in the lake basin.

There are four possible sources for rain-out sediment: ice-bergs, a floating or undermelted ice margin, and pack ice.

a. Ice-berg sedimentation has been observed in modern glaciomarine environments

(Ovenshine, 1970; Powell, 1981, 1983), however, berg-deposits are the result of sediment dumping as top-heavy bergs roll over and form lenses of sand and gravel. Clasts observed in lithofacies SD predominantly occur singly, so that an ice-berg source is unlikely.

b. Deposition from a floating ice margin is also theoretically possible and could form a diamicton with abundant fines, similar to the diamicton of lithofacies SD (Fig. 4.6 c).

Modern sediments that are interpreted to be the product of rain out by melting out from floating ice are characterized by stratified and unlayered diamicton (Anderson, 1983). Production of the regular, relatively fine lamination of subfacies SD-L by rain out requires cycles of rain out followed by more quiescent periods to allow settling of fines.

It is estimated that 135 m of water could have been ponded in front of the glaciers that advanced into the area. Therefore, floating ice along the glacial margin was possible, especially over valleys, where water depths could have exceeded 200 m. Debris would have been carried predominantly at the base of the floating ice and rain out would occur as it melted.

It is also conceivable that the glacier detached from its bed due to undermelting, creating a low cavity in which rain out and debris-flows could deposit sediment.

d. Winter lake-ice could also have provided a means to transport and deposit sediment by rain out (Fig. 4.7). Debris that is transported by pack ice has two possible sources.

(i). From debris-flows, slumps, and fluvial transport onto the surface of lake ice.

(ii). By freezing on to the base of grounded ice.

The first debris-source mechanism (i) is relatively simple, requiring that surface glacial melting occur before breakup or complete melting of proglacial lake ice cover, thus enabling supraglacial sediment to become unstable and mobilize, redepositing on lake ice. This may also have occurred where sediment was carried by spring runoff streams that flowed out onto lake-ice from glacial and periglacial areas, as well as by wind during winter and spring.

To understand the freezing on mechanism (ii), we must first reconstruct the lake basin. Of particular importance are the extensive areas of shallow water that must have existed along the western and southern shorelines, on the opposite side of the lake from

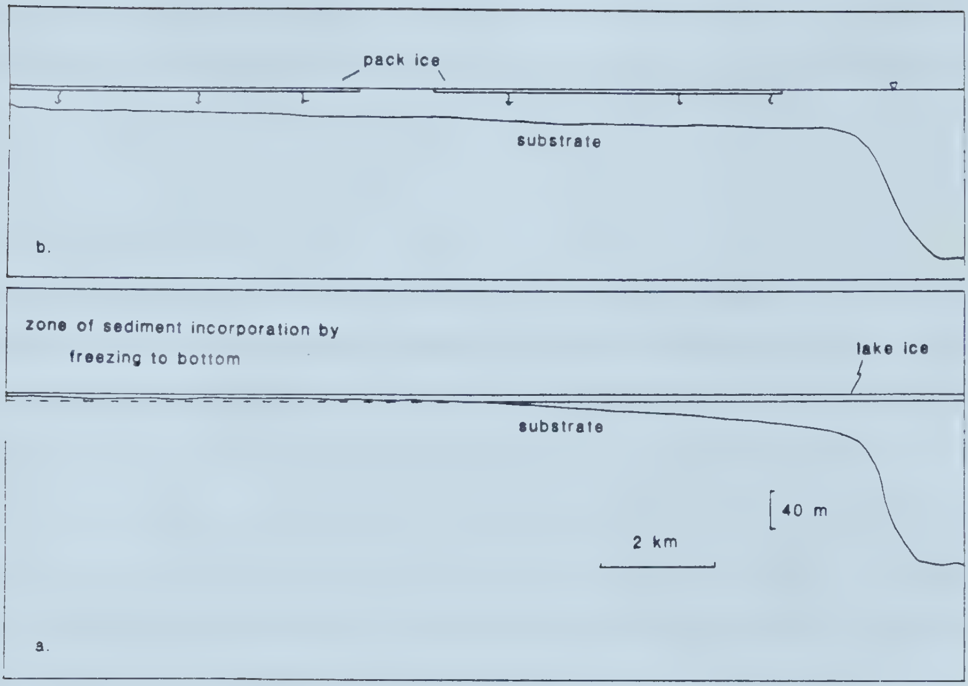


Figure 4.7. Schematic diagram showing the deposition of lithofacies SD (stratified diamicton) from floating pack ice.
a. In late fall, the lake freezes over and freezing penetrates the lake bottom in extensive shallow areas along the periglacial shoreline.
b. In spring, the lake level rises due to an influx of meltwater, causing lake ice that was frozen to the lake bottom to float. It carries sediment frozen to its base and rafted on top of it, which subsequently melts out as the pack ice moves around the lake, driven by wind and currents.

the glacier, where there were very gentle lake bottom profiles parallel to the modern flat prairie surface. In fall, lake levels would drop and then as winter lake-ice formed, freezing would extend into the lake bottom wherever water was shallow enough (less than 2 to 3 m). When spring temperatures began to rise, surface melting on and off the glacier would raise the lake level, floating previously grounded lake-ice and sediment that was frozen to its base.

Formation of stratification

A continuous rain out of large quantities of sediment does not produce a stratified deposit (Anderson, 1983). Periodic reductions in the rate of sedimentation are needed. An ice margin could provide abundant sediment with stratification forming during brief local sedimentation hiatuses when clean ice bands were exposed at the base of the ice margin. Cycles of rain out followed by quiescent periods might also occur by deposition from an ice pack that moved around the lake basin, staying in any given locality for varying amounts of time ranging from hours to days or weeks. Larger clasts would drop off as they were released by melting and would be deposited singly.

Therefore, the debris-laden ice margin and pack ice could produce a deposit resembling lithofacies SD, which would have an inconsistent orientation of microclasts, caused by their fall-out mode of deposition. Where lithofacies SD has a preferred orientation (Fig. 2.4: e) and it contains undraped clasts, it is likely that resedimentation by slumps and flows redistributed most of the rained out sediment.

3. Basal melting out from a glacier

The basal melt-out mechanism was considered in the foregoing discussion of the genesis of lithofacies UD. To evaluate whether the subglacial environment has any merit as an environment of deposition of lithofacies SD, the most critical problem involves the probability of depositing stratified diamicton from a subglacial position.

Most diamicton that melts out at the base of modern glaciers is unlayered or contains small irregular, discontinuous, deformed silt, sand, and gravel lenses (Boulton, 1970a; Kruger, 1979; Lawson, 1979b). Undeformed, laminated and bedded melt-out diamicton similar to subfacies SD-L (Plates 2.11, 2.12, 2.13, and 2.14) have not been

observed in the modern glacial environment. However, interbedded debris-rich and clean ice bands have been reported in the basal zone of modern glaciers (Gow *et al.*, 1979; Herron and Langway, 1979; Lawson, 1979b). These bands typically differ in grain size composition.

Shaw (1979) observed relatively undeformed, well layered till that was deposited by sublimation from layered basal debris-rich ice of the Taylor Glacier in Antarctica. However, there is abundant evidence for the former presence of water in lithofacies SD sediments (discussed above), so that sublimation is unlikely to have been a major mechanism.

It is theoretically possible to deposit stratified diamicton by melting out at the base of the glacier. Shaw (1979: 413), in a discussion of stratified (Sveg) till genesis, described a basal melt-out mechanism that deposits sediment that is

> ...stratified with layers of sorted material interspersed with layers of diamicton. Individual layers may extend laterally over 10 m or more.... Complex interfingering of diamicton and stratified sediments is found in association with thicker stratified sand beds.... The sorted sedimentary layers are inevitably deformed over large clasts in steep-sided drapes. The overlying stratified beds are commonly undeformed where a clast has about the same or lower dimensions than an enclosing diamicton bed. However, deformation occurs where a clast cross-cuts a sorted layer.

Shaw (1979: 414, 415) interpreted the stratified diamicton sequence as having been deposited by the process of basal melting out from a stagnant ice mass. He suggested that the melt-out process is influenced by the stratification of debris with clean ice, such that stratified sorted sediment would be deposited in cavities within melting ice layers. As the ice melted, differential subsidence around large clasts in these initially horizontal, sorted layers would then have lead to draping of stratification over underlying clasts (Fig. 4.8). Furthermore, he stated

> ...if the ice in a debris rich band is merely interstitial, meltout involves no differential subsidence around clasts enclosed in the band.

Lawson (1979b) reported debris-band concentrations in stratified ice of up to 74 percent by volume in the basal debris-zone of the Matanuska Glacier. In his discussion of alternative interpretations for the genesis of stratified diamicton (Sveg till), Shaw (1979: 416) stated

> The obvious alternative that diamictons are flow tills is contradicted by the

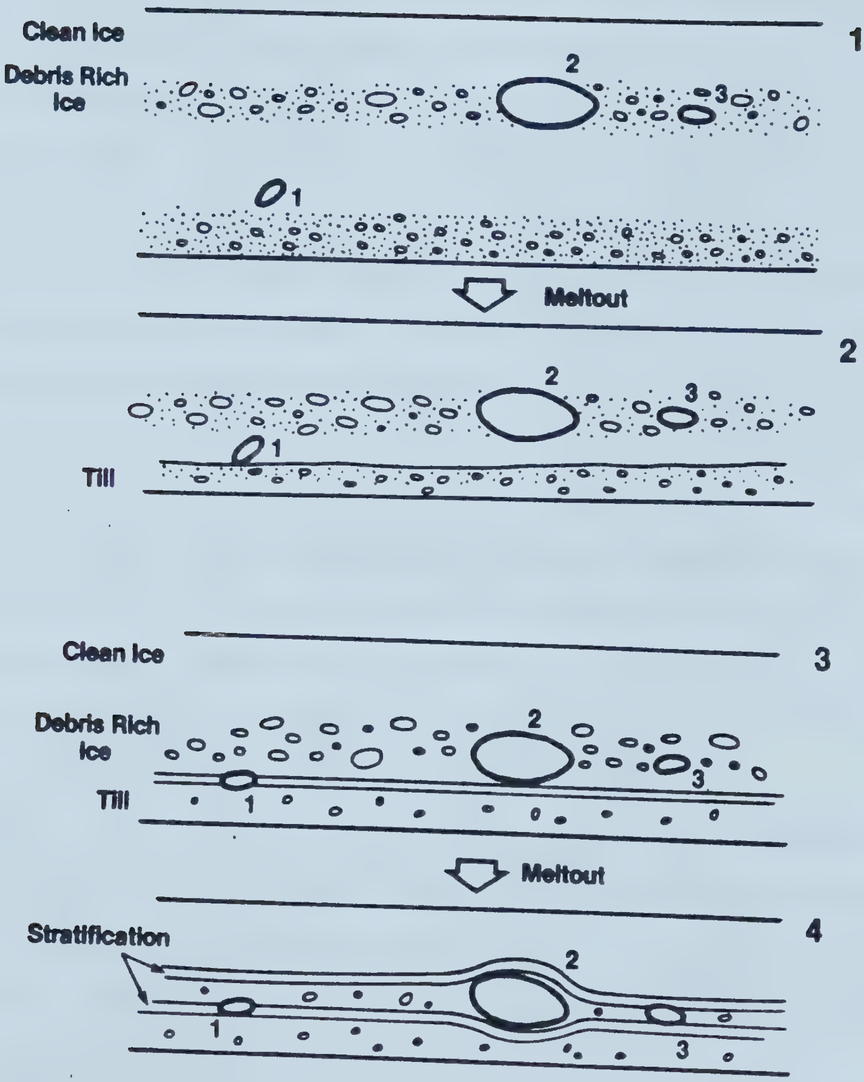


Figure 4.8. Schematic diagram showing the deposition of lithofacies SD (stratified diamicton) by basal melting out (after Shaw, 1979).

structural relationships between clasts and stratified units and by the consistent orientation pattern of clast long axes.

The stratified diamicton of subfacies SD-L has all of the characteristics noted by Shaw, with three important exceptions.

a. Microfabric data from lithofacies SD-L diamicton samples have a polymodal orientation with no consistency between diamicton beds within a single unit (Fig. 2.4: a-d). Therefore the consistent orientation of pebbles in Shaw's study imparted by flowing ice is not evident in subfacies SD-L at least not in the microclast (less than 1 mm) size range.

b. The deformation of sorted bands below larger clasts is not described by Shaw (1979). This deformation can be up to about one half of a clast's diameter in lithofacies SD (Plate 2.14). If this deformation were caused by differential subsidence, then any subsidence greater than an enveloping diamicton bed thickness would affect adjacent bedding planes. The even, planar nature of the bedding in subfacies SD-L would require very consistent debris concentrations in the basal ice zone, even where large clasts were not present. This consistency is possible in stratified basal ice over the relatively short distances (10 to 20 m) of undeformed stratification observed in outcrops of lithofacies SD, but it is unlikely that this was the case everywhere SD was deposited. It is also conceivable that these large clasts and the sorted sediment were dropped into a relatively large cavity at the base of inactive ice, as discussed for the multiple debris-flow hypothesis.

The lowering of a glacier onto its bed so that some clasts were pushed into the substrate thus deforming it in the manner observed under many pebbles and cobbles in lithofacies SD is plausible during melting out (Fig. 4.6 b). However, the basal ice could no longer have been flowing because lithofacies SD shows no evidence of deformation caused by dragged cobbles (Boulton, 1976).

c. The presence of undeformed, rounded soft sediment clasts (clay and silt) in lithofacies SD is not easily explained by the basal melt-out hypothesis. That is, glacial incorporation and abrasion of clay and silt to form rounded clasts that were subsequently deposited without obvious deformation is unlikely, given the high shear environment that these clasts would have had to survive (Boulton and Eyles, 1979; Boulton, 1979). It should be noted, however, that soft sediment clasts are rare.

In summary, the broad lateral extent of lithofacies SD, on the order of 1.5 km or more, would require consistent basal conditions (melting and drainage) and debris content over this area. There is no evidence from modern glaciers to support this degree of consistency, which may also have been rare in Pleistocene continental glaciers. Furthermore, the apparent greater proportion of angular pebbles in lithofacies SD is an unlikely characteristic for subglacially transported clasts. Therefore, even where fabric data are not available to show the lack of. or variation in preferred orientation observed at DNP79-11 (Fig. 2.4), the special and likely rare conditions discussed above make basal melting out a complex process and much less probable than the debris-flow hypothesis.

Summary

Lithofacies SD (stratified diamicton) could have been deposited as follows:

1. In a proglacial lake from debris flows with possible sediment contribution by raining out from a floating ice margin or pack ice.
2. In a subglacial cavity or cavities by debris-flow and sediment fall from the base of the ice.

D. Diamicton containing lenses (DCL)

Melting out from a supraglacial position

Where lithofacies DCL is found at the top of a diamicton sequence, as it is in the upper member of formation B at Evilsmelling Bluff (Plate 2.17), it is interpreted to be a supraglacial melt-out complex sediment that was let down as underlying ice melted. The term *supraglacial* is used to refer to the glacial position from which sediment is deposited. It does not refer to the position of transport. Therefore, supraglacial melt-out sediment is an accumulation of debris that occurs as the upper clean ice melts away to expose basal debris.

Studies on modern glaciers and their deposits have documented sediment types and associations in the supraglacial environment of retreating or stagnant glaciers (Boulton, 1968; N. Eyles, 1979) that closely resemble lithofacies DCL sediment. In this environment, differential melting produces oversteepened slopes and saturated debris that periodically

flows, slumps, and slides. Meltwater streams and ponds deposit channel sand, gravel, and laminated sediment. As melting proceeds, these deposits become unstable and move by gravity into depressions (N. Eyles, 1979). In the final deposit, most of the sediment has been recycled, that is, locally resedimented several times. The presence of normal faulting and synformal deformation in lenses and beds within lithofacies DCL suggests that this type of deformation occurred by collapse (McDonald and Shilts, 1975). The most likely cause of collapse was the melting out of underlying ice (Haldorsen and Shaw, 1982; Shaw, 1982). The lenses of sand, silt and gravel within the diamicton of lithofacies DCL that are relatively intact, probably formed late in the supraglacial melt-out process, so that little resedimentation acted to destroy bedding and structures.

Melting out from the base of a glacier

Studies on modern glaciers (Boulton, 1970a, 1972b; Shreve, 1972; Lawson, 1979b) have shown that basal debris-laden glacier ice commonly melts differentially, producing cavities along which escaping meltwater flows. In many places, sorted sediment, including fine gravel, sand, and silt, is deposited in these cavities after debris has been melted and winnowed out of the ice (Shaw, 1979). If this deposition occurs within static, basal stratified ice (Lawson, 1979b; Shaw, 1979, 1982; Haldorsen and Shaw, 1982), the sorted sediment is preserved as irregular discontinuous lenses within diamicton. Differential melting out and variable debris concentration in the ice cause slight deformation of the stratification. This leaves a deposit with characteristics that are very similar to the less deformed parts of lithofacies DCL. In addition, the preservation of these lenses and stratification in a relatively undeformed state suggests that no basal shearing due to ice flow occurred during or after deposition.

E. Deformed stratified diamicton (DSD)

The occurrence of uneven discontinuous clay, silt, and silty sand beds within and interdigitized with diamicton beds in lithofacies DSD suggests simultaneous or rapidly changing depositional processes (Marcussen, 1975; N. Eyles, 1979; Lawson, 1979b; Haldorsen and Shaw, 1982; Shaw, 1982).

There are two different types of inclusions in lithofacies DSD at Golden Valley Bluff.

a. Large deformed sandstone blocks are interpreted to have been glacially incorporated locally.

b. Deformed silty sand lenses that have upturned ends with vertical stringers extending from them (Plate 2.18) occur throughout the unit. It is possible that these lenses were glacially incorporated from pre-existing silt and sand beds in a frozen state. Microfabric analysis of diamicton shows a broad unimodal trend throughout most of the unit (5 samples were analyzed). Figure 2.6 (a, b and d) shows a consistent broad northeast-southwest trend in a vertical sequence suggesting that sedimentation occurred subglacially, so that a preferred orientation of grains was preserved from the glacial basal debris (refer to the discussion of lithofacies UD, in this chapter). However, the entire outcrop has deformation of stratification that resembles collapse or injection structures (Reineck and Singh, 1980; Postma, 1983).

Therefore, it is hypothesized that the disruption of subglacially deposited sediment (Plate 2.18), occurred as saturated sediment was forced upwards through some parts of lithofacies DSD. This might have happened in response to pressure release when the sediment was loaded by overlying ice, probably in association with a rapid increase in the rate of subglacial drainage. Disruption was concentrated along conduits, leaving the intervening sediment relatively undisturbed. It is also possible that disruption occurred when buried ice-blocks melted out of the sediment, causing collapse and injection around the cavity left by the block.

F. Layered Diamicton (LD)

Lithofacies LD is unusual in that its layers are not obviously sedimentary, unlike the stratification in lithofacies SD and DSD. The layering is interpreted to be a glacigenic deformation lithofacies in which subglacial shear has been the predominant process. The following observations support this hypothesis:

1. The presence of horizontal and oblique fractures.
2. The presence of microfaults with horizontal displacements (Plate 2.20).
3. The presence of recumbent folds.

4. The presence of discontinuous layers of diamicton, sand, and silt that have an attenuated geometry in some places (Plate 2.19).
5. The lack of sedimentary structure throughout the layering.
6. A unimodal or bimodal microclast orientation distribution in some samples (Fig. 2.7: d, e, i, j).

All of these characteristics could have formed during shear deformation with a predominantly horizontal component that operated on pre-existing sediment, as well as during basal melting out and lodgement. Similar structures have been described by Berthelsen (1979), Boulton (1979), and Kruger (1979). Sedimentary structures, especially in sand and silt units, could have been destroyed by deformation within the units during shear deformation.

G. Interbedded diamicton, sand, and silt (IDSS)

Interbedded diamicton, sand, and silt -- Tabular

Lithofacies IDSS-T sediment is interpreted to have been subaquatically deposited. The close association of unlayered and convolute diamicton sand, and silt in this interbedded sequence suggests that they were deposited in the same highly variable environment. Unlayered beds were probably deposited from moderate-velocity (low water content) flows that did not allow internal sorting (Middleton, 1976). The agglomerated diamicton-ball structure of some beds (DNP82-100) is probably the result of a mass slump that originated in a semiconsolidated diamicton bed that broke up as it moved down-slope. The horizontal bedded and cross-laminated sand that sharply overlies each diamicton bed (DNP82-100) was likely deposited by turbidity currents (discussed under the genetic interpretation of stratified diamicton, lithofacies SD). However, in places, sand beds contain or grade upwards into laminated silt beds or laminae that were probably deposited in quiescent water.

Similar laminated silt beds have been documented at the top of turbidity current deposits in marine environments, where they have been interpreted as suspension rain-out sediment deposited from silt and fine sand turbulence clouds following the cessation of a

turbidity current (Hampton, 1972; Middleton and Hampton, 1976). Another possible source for this laminated silt is settlement from sediment-charged, quiescent water. However, turbidity currents are required to deposit the sorted sand where flow structures such as cross-beds and laminae are present (DNP82-100).

In summary, the possible depositional environment of lithofacies IDSS-T include the following:

1. A diamicton source that periodically became unstable and slid or flowed into the local basin, depositing diamicton.
2. A repeated or continuous deposition of sand and silt by turbidity currents and density underflows.

Interbedded diamicton, sand, silt, and gravel -- Lenticular

Lithofacies IDSS-L is presently being deposited in alluvial fans at the mouth of gullies that drain into the South Saskatchewan River. The following interpretation is based on limited observations. Active sedimentation of diamicton, sand, silt, and gravel and erosion occur only during rainstorms. Diamicton is deposited by mud-flows that are rarely more than 10 cm thick. Subsequent water-flow erodes small channels on top of and between flow deposits forming cut-and-fill structures (Plate 2.21). Angular blocks of pre-existing sediment ranging up to 2 m across (Plate 2.22) fall onto the surface of the fan and are subsequently covered by mud-flow sedimentation.

V. GENETIC INTERPRETATION OF THE MEDICINE HAT AREA QUATERNARY STRATIGRAPHIC SEQUENCE

The sedimentary lithofacies found within the Quaternary lithostratigraphic seqence in the Medicine Hat area and the genetic interpretation for each have been discussed in earlier chapters. These interpretations are based on the characteristics of individual lithofacies with minimal reference to lateral or vertical lithofacies relationships. However, the interpretation of sedimentary lithofacies must include the relationship between adjacent lithofacies (Visser, 1965; Walker, 1979). This chapter combines stratigraphic and lithofacies observations and genetic interpretations into the most likely genetic sequence of events for the entire Quaternary succession. No attempt is made to develop a chronology, because no new dateable material were collected. However, correlation with the existing litho-biostratigraphic interpretation developed by Stalker (1976, 1983) is discussed in the next chapter.

A. Preglacial Events (PG)

Event PG-1

As previously mentioned, the base of the Quaternary sequence in the Medicine Hat area is defined by an erosional unconformity and the sands and gravels of the lower member of the Empress Formation. This unit contains no material derived from the Canadian Shield and therefore is interpreted to predate any incursion of Keewatin ice or its meltwaters into the region. The sparse outcropping of this member in the area has prevented any sedimentological interpretation. However, it is known from testholes to be mainly a coarse quartzitic gravel, probably fluvial in origin.

Event PG-2

A consistent change in sediment character from cobbly gravel to sand and silt at the top of the lower member of the Empress Formation throughout the area likely records a dramatic alteration in river gradient or the loss of a quartzitic-cobble source. The contact between the middle and lower members is sharp in testholes (Fig. 3.6) and suggests a depositional hiatus. About 55 km to the west of the study area, along the South

Saskatchewan River northeast of Bow Island (Fig. 1.1), probable permafrost sand wedges in the top of the lower member support this discontinuity hypothesis (Proudfoot, *in preparation*). The time span of this depositional break is unknown.

This part of the sequence is well exposed along the east end of Mitchell Bluff and the north end of Golden Valley Bluff and is shown schematically in Figure 5.1. The interbedded sand, silt, and clayey silt lithofacies of the middle member of the Empress Formation underlies most of the exposed cross-bedded sandy lithofacies observed in the area and also occurs interbedded with it in several testholes (Fig. 3.3). The laminations within the silt indicate that it was deposited in quiescent water. In places (DNP80-52+53, DNP79-17), this lithofacies is interbedded with cross-bedded sand that must have been deposited by flowing water. Wood, including a small stump in growth position along the north end of Golden Valley Bluff about 30 m north of DNP79-17, and abundant small twig or root segments within the clayey silt and sand provide evidence for vegetation. This combination of lithofacies is interpreted to be fluvial overbank sediment deposited in a floodplain that occupied much of the preglacial valley floor. No detailed sedimentological study was carried out on this unit, so that this interpretation has not been refined.

The reason for the depositional break or the change to a sand-dominated fluvial system is unknown. It is possible that the climatic cooling that caused the development of permafrost features in the top of the lower member of the Empress Formation may have been associated with the beginning of Cordilleran or Keewatin glaciation. This lower temperature could have greatly reduced rainfall and summer meltwater (inferred from sand wedges), thereby decreasing the amount of water available to the fluvial system. However, a change in sediment source to predominantly sand from gravel could also have occurred.

The sand that composes the cross-bedded lithofacies of the middle member of the Empress Formation does not contain material derived from the Canadian Shield. Available data are inadequate to properly interpret the local depositional environment. However, the depth of scour and the thickness of climbing ripple beds in the sandy lithofacies would have required at least several metres of water depth to form. It is possible that much of this sandy lithofacies was deposited in a fluvial environment as the river gradient shifted to accomodate the development of the nearby proglacial lake in which the upper member was deposited. The complete lack of coarse gravel in the sandy lithofacies, although there

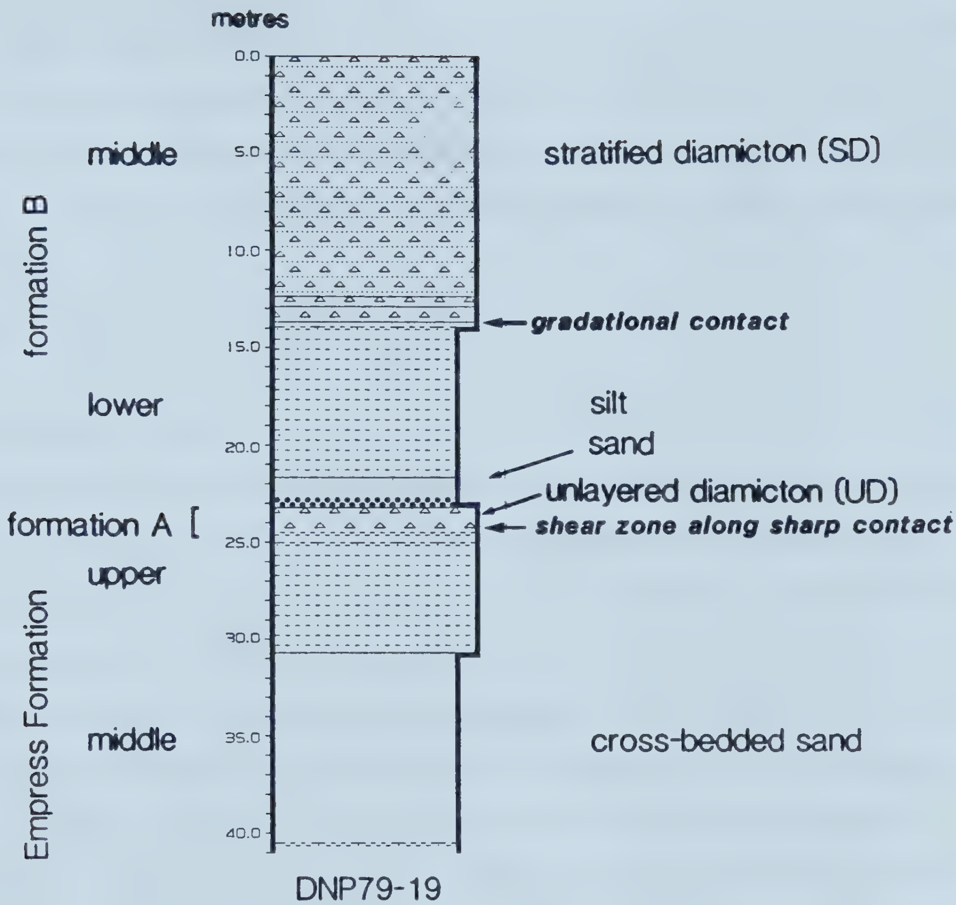


Figure 5.1. Lithofacies sequence within the lower and middle members of the Empress Formation at the north end of Golden Valley Bluff.

was an abundant supply in the underlying lower member, indicates that water velocities were insufficient to transport gravel, or that a reduction in river gradient diminished bed erosion. In a few places (Plates 3.1 and 3.2), relatively small silt lenses in the sandy lithofacies indicate that some ponding occurred, probably in small abandoned channels and on the floodplain. Elsewhere, the presence of numerous pebble-sized silt and clay rip-up clasts in infilled scours suggest that silt beds previously deposited on the river bank or in abandoned channels were occasionally undercut or ripped up. It is likely that this happened during periods of flooding and when flow shifted back into abandoned silted-up channels.

B. Phase One Glaciation

Proglacial sedimentation

The gradual upwards transition to the parallel laminated silt and the rhythmically bedded silt and clay cap of the upper member of the Empress Formation (Fig. 5.1) indicates a major change in the depositional environment. The weakly laminated silt and the silt and clay rhythmites found along the north (Fig. 5.1) and south ends of Golden Valley Bluff (Plates 3.1 and 2.5), the east end of Mitchell Bluff, and in several testholes (eg. Fig. 3.6) were deposited in a lake that formed when the preglacial South Saskatchewan River system was dammed. Although an earth dam formed by a landslide might have accomplished this locally for a short period of time, the thickness of this silt and silt-clay sequence (up to 12.4 m), and the fact that the river did not re-establish in this channel, as it did when the silt lenses of the cross-bedded sandy lithofacies were eroded or covered, suggests that a longer, regional blockage occurred. This could only have been effected by the advance of a continental glacier into the region from the northeast, north, and east. The rhythmites that occur at the top of the upper member resemble those deposited in proglacial lakes (Plates 2.3 and 2.5).

The gradual fining upwards of the upper member of the Empress Formation to the abrupt basal contact of the till of Formation A is the reverse of most proglacial lake coarsening upwards sequences that are deposited in front of an advancing glacier (Flint, 1971). The water that formed the lake or at least the sediment that was deposited in it, probably had a predominantly nonglacial source to the west, and not as is commonly the

case, from a glacial source. This is interpreted from the lack of material derived from the Canadian Shield in the base of the silt, and their sporadic occurrence throughout the upper part of this unit. The lake level rose, partially in response to an increasing volume of water and also due to the continued approach of the glacier that displaced the lake westwards and blocked outlets. This presumably caused the sediment source at the river mouth to migrate upstream away from the Medicine Hat area. Therefore, at least the upper part of the cross-bedded sandy lithofacies and the interbedded silt and sand that overlie it were deposited relatively near the river mouth. However, through time, this source moved westwards and the finer fraction was transported to this area from more distant glacial and nonglacial sources, as indicated by the silt, clayey silt, and silt-clay rhythmite lithofacies. These rhythmites likely required a glaciolacustrine environment to form. Load structures (Plate 3.4) in the silty lithofacies probably formed during rapid sedimentation from density underflows that carried fine sand and silt into the basin.

The absence of a proximal proglacial coarsening upwards sequence at the top of the upper member of the Empress Formation is more puzzling. It is possible that such a succession was not deposited. This could have occurred if the advancing glacier had little melting associated with it, or if there was only a small volume of sediment available to be transported lakeward by meltwater. There is little evidence to support this hypothesis.

An equally plausible explanation involves the deposition of a coarsening upward proglacial sequence and its subsequent complete erosion by the advancing glacier that deposited formation A. There is some indirect evidence to support this hypothesis.

1. The scratched, fractured and drag-folded basal contact of formation A represents a shear zone that formed as the base of the glacier overrode the substrate (discussed in chapter 4). The rhythmites may have acted as a plane of decollement during this deformation.

2. The high concentration of clay and silt smudges in the basal 10 to 20 cm of formation A till, where it directly overlies clay and silt beds at the north end of Golden Valley Bluff, indicate that glacial erosion of the upper part of the Empress Formation probably occurred.

Glacial sedimentation

The diamicton that occurs along the base of formation A (Fig. 5.1 and Table 5.1) is commonly unlayered (lithofacies UD). This sediment likely formed subglacially from the Phase One glacier, probably by melting out from stranded debris-rich ice blocks or by lodgement or basal molding (discussed in detail in chapter 4). This interpretation is based on the two points cited above, its basal position within the diamicton sequence, and the fact that it lies directly on a sharp erosional basal contact. The presence of delicate silt and clay smudges that in places extend up from the substrate within the basal 10 cm indicate that deposition probably occurred within a short distance of incorporation.

The thickness of lithofacies UD ranges from about 50 cm along the north end of Golden Valley Bluff (Plate 3.1), where it has been thinned by fluvial erosion, to about 12 m at the east end of Island Bluff (Plate 3.8). Unfortunately, there are no other laterally extensive outcrops of lithofacies UD. Along the east end of Island Bluff (DNP79-6), lithofacies UD contains a single sand and silt horizon (Plates 3.8 and 3.9). This is possibly a glaciotectonic structure that resulted from the remobilization of previously deposited blocks of diamicton and silt.

Lithofacies DSD gradationally overlies UD sediment in formation A at Golden Valley Bluff (Fig. 5.2) and is also interpreted to have been deposited subglacially for the following reasons:

1. The broad unimodal trend of microclast orientations throughout lithofacies (DSD, Fig. 2.6) that parallel microfabric preferred orientations measured in lithofacies UD.
2. The gradational basal contact with lithofacies UD (DNP78-14).

The abundant deformed sand and silt lenses and beds within lithofacies DSD at Golden Valley Bluff (Plate 2.18) are interpreted to have been postdepositionally formed by sediment collapse and injection from beneath or within the bottom part of the lower member of formation A. This could have occurred during or after the deposition of lithofacies UD by pressure release (Fig. 5.3) of subglacial water.

A possible alternative interpretation involves the collapse of lenses and beds within the diamicton as large buried ice blocks melted out. The apparently consistent preferred orientation of microclasts within this lithofacies would not have been preserved unless resedimentation due to collapse and injection was localized. The absence of lithofacies

Lithofacies and nature of contact	Stratigraphic Position	Genetic Interpretation	Depositional Environment
IDSS-T	top of formation A	*deposition from subaquatic debris-flows with repeated or continuous deposition of sand and silt by turbibity currents and/or density flows	beneath a floating ice margin proglacial lake
DSD	middle of formation A	*subglacial deposition and subsequent disruption by injection from below subglacial deposition and subsequent collapse as buried ice melted out	subglacial deposition by flowing or inactive ice and subsequent disruption under inactive ice subglacial deposition by flowing ice and subsequent collapse
UD <----> >>>>	base of formation A	* basal melting out * subglacial lodgement * subglacial molding	subglacial by flowing ice subglacial by flowing ice subglacial by flowing ice
DCL	top of formation B	*depositon from a supraglacial position as underlying ice in the basal debris zone melted out; sediment flows common	supraglacial
UD	base of upper member of formation B	* basal melting out * subglacial lodgement * subglacial molding	subglacial by flowing ice subglacial by flowing ice subglacial by flowing ice
>>>> SD/IDSS-T	upper part of middle member of formation B	SD *debris-flows with some sediment contribution by rain out IDSS-T: * deposition by subaquatic debris-flows and underflows	pro or subglacial lake, with rain out from ice (floating or undermelted); distant from subglacial water outlets on or near subaquatic fans in beneath or adjacent to glacier
LD >>>>>>>	base of middle member of formation B	formed by subglacial shear of pre-existing and continuously depositing sediment	subglacial

Table 5.1. Summary of the genetic interpretation of the lithofacies sequences determined for formations A and B.

*	favoured interpretation	---	gradational contact
>>>	glaciotectonic deformation	___	sharp contact
<---->	scratched and polished surface	/	lateral lithofacies equivalent

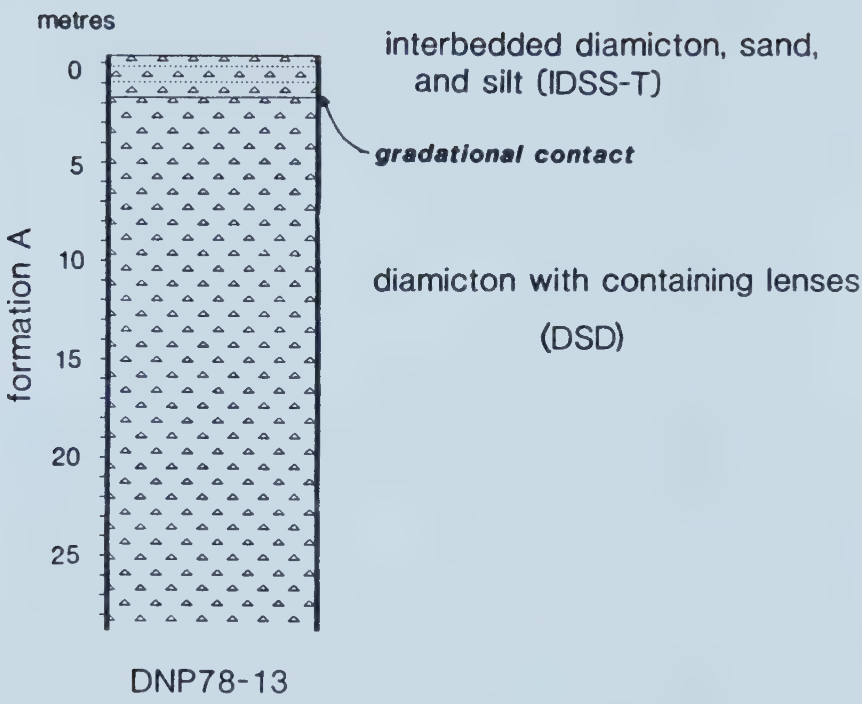
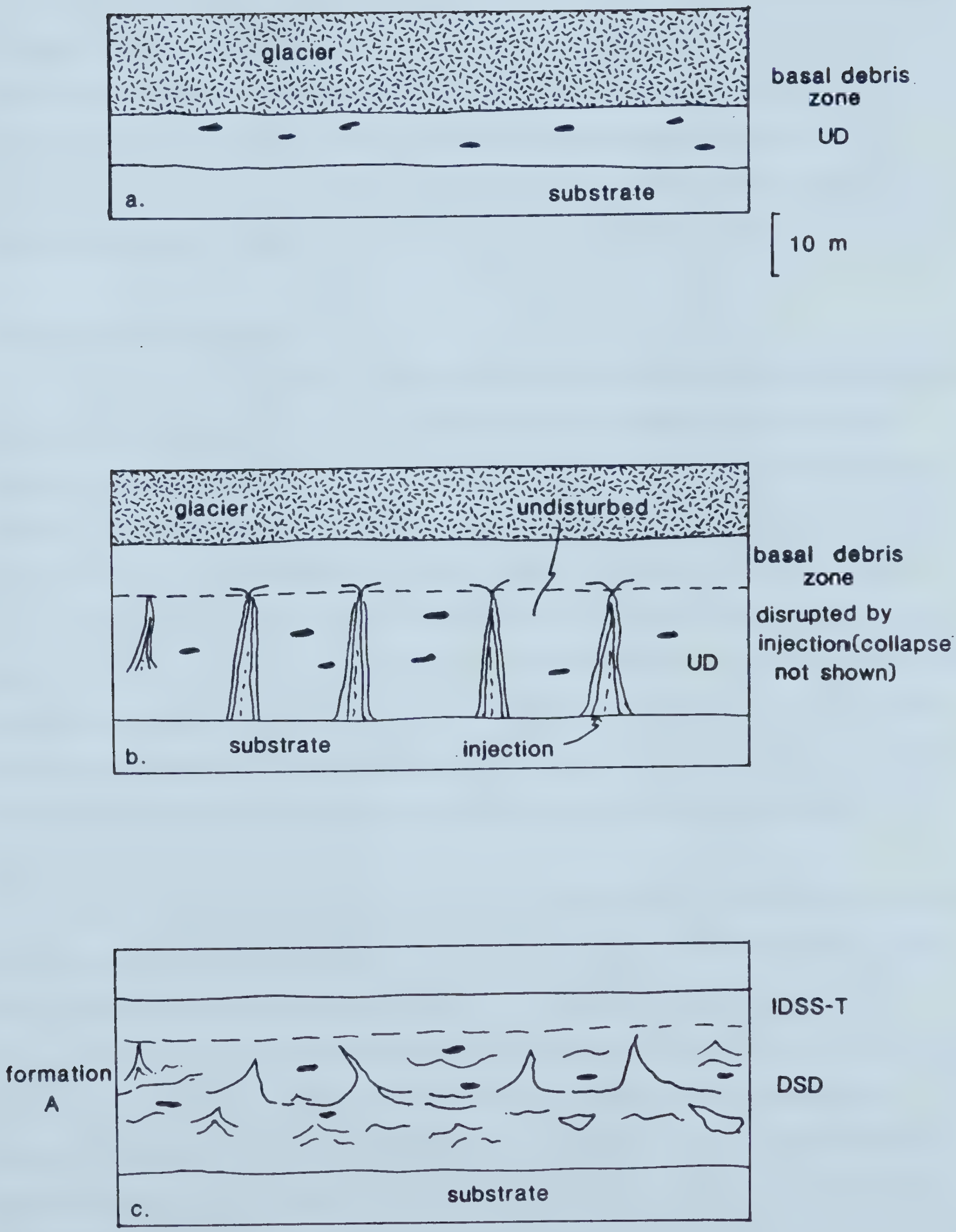


Figure 5.2. Lithofacies sequence within formation A at Golden Valley Bluff (DNP78-13).

Figure 5.3. Schematic diagram showing the formation of lithofacies DSD (deformed stratified diamcton) subglacially. It involves two phases. a. Deposition of diamicton subglacially. b. Disruption of basal diamicton by sediment injection from below this diamicton, or collapse as buried ice melts out. c. The resulting sequence of tabular interbedded diamicton, sand, and silt (lithofacies IDSS-T) overlying deformed stratified diamicton (DSD).



glacier
basal debris zone
UD
a.
substrate
10 m
glacier
undisturbed
basal debris zone
disrupted by injection(collapse not shown)
UD
b.
substrate
injection
IDSS-T
formation A
DSD
c.
substrate

DSD in formation A at Island Bluff is likely due to a lateral lithofacies change, although the presence of probable sheared silt bands at this site could also indicate that the upper part of formation A has been removed or modified by overriding of the same glacier.

The occurrence of lithofacies IDSS-T, tabular interbedded sand, silt and diamicton, at the top of formation A (eg. DNP78-13, Fig. 5.2 and Plate 2.18) is interpreted to be ice-proximal proglacial / supraglacial lake sediment. It was presumably deposited during glacial retreat (discussion Chapter IV). However, it is also possible that these IDSS-T sediment formed subglacially as the injected sediment that created the deformation reached the base of the glacier and was forced to flow laterally (Fig. 5.3 b).

C. Interglacial / Interstadial

The Phase One deglaciation of the area was followed by a period of fluvial erosion and deposition as evidenced by the lag gravel and cross-bedded sand of the lower member of formation B, which is exposed at the north end of Golden Valley Bluff (Fig. 5.1 and Plate 3.1) and the east end of Mitchell Bluff, and by the sand exposed at Evilsmelling Bluff (DNP79-11, unit 3 and DNP79-14, unit 1; Plate 3.10 and Fig. 5.4). This nonglacial river created the valley system that is shown in Figure 3.2 where it cut into and in places through formation A. Outside of this subsequently infilled valley, the unconformity is much less prominent. At the east end of Island Bluff (DNP78-4, units 3 and 4), it is represented by 10 cm of pea gravel overlying a 70 cm silt bed. The silt bed was probably deposited on a flood plain during a particularly high water flow event or prior to the development of deeper valleys.

At Bain Bluff (DNP 78-9, units 2 and 3) the lower member of formation B consists of a sandy well-sorted gravel that has well developed bedding, and is overlain by a very poorly sorted coarse sandy gravel (Plate 3.11). The basal portion of this gravel is interpreted to be a channel lithofacies of the lower member of formation B. The chaotic, poorly sorted upper 3.8 m of this unit has several possibile origins. It gradationally overlies well sorted gravel and so was probably deposited in the same environment. This gravel could have been produced by bank slumping, fluvial reworking or frost action. There is insufficient data to be more definitive. It is unlikely that it was deformed by the glacier that deposited the diamicton that sharply overlies it, because there are no

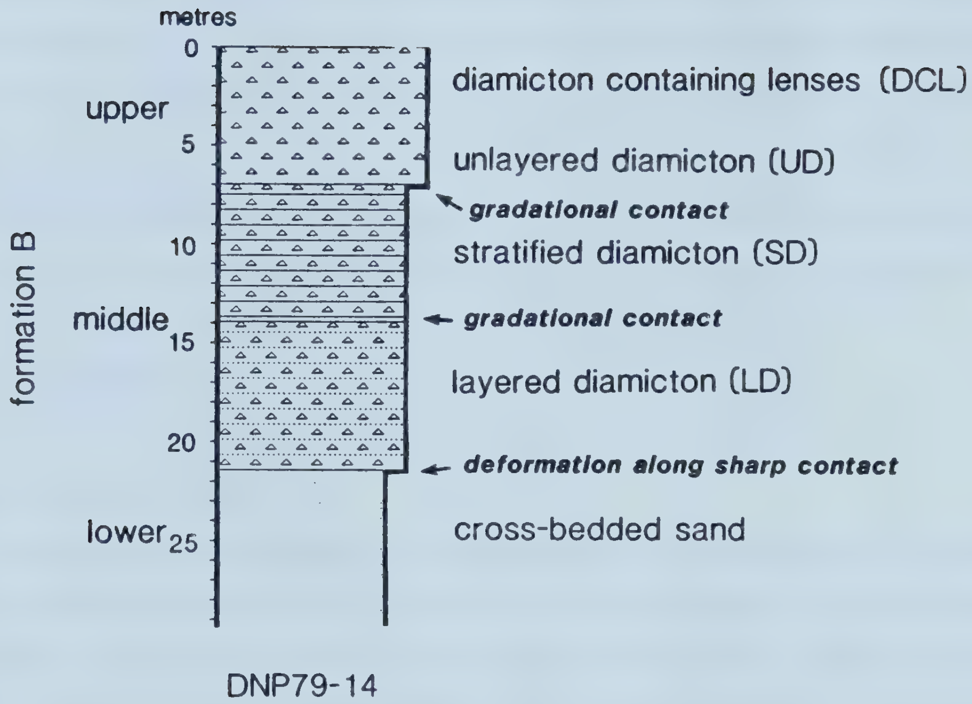


Figure 5.4. Lithofacies sequence and associated structures within formation B at Evilsmelling Bluff (DNP79-14).

drag-style deformation structures or fractures within the gravel to support this hypothesis.

Along the central part of Golden Valley Bluff (Plate 5.1), overlying the erosional unconformity at the top of formation A, is the lower member of formation B. This unit comprises a lag gravel and an overlying medium to fine grained cross-bedded sand (1 to 2 m thick) that has synformal collapse structures, interpreted to be the result of subsidence into depressions left as small included ice blocks melted. The origin of this ice was not necessarily glacial. It is equally likely that river ice was buried during early spring run-off and these features formed when it melted. The overlying silty sand unit (unit 5, DNP81-6, Plate 5.1), shows no such deformation, indicating that it was deposited after the ice blocks melted. This silty sand is interpreted to be a flood plain deposit associated with the fluvial system that developed during deposition of the lower member of formation B.

D. Phase Two Glaciation

Proglacial sedimentation

The fining upwards sequence of sand and silt of the middle member of formation B (Table 3.1) probably resulted from the damming of regional drainage, forming a proglacial lake. Therefore the environment that developed was similar to that in which the upper member of the Empress Formation was deposited. The source for most of the sediment that was deposited during the initial stages of this proglacial lake was again to the south and west. Initial sedimentation in the lake basin was probably near the mouth of the nonglacial South Saskatchewan River, resulting in a predominantly silty deposit.

Glacial sedimentation

Two hypotheses are explored to explain the lateral and vertical lithofacies associations within the middle and upper members of formation B. They are both considered because of the variation in the nature of the contact between the middle and upper members of formation B, which in places is gradational (Figure 5.4) and elsewhere is sharp and likely erosional (Figure 5.5).

1. The lithofacies sequences depicted in Figure 5.4 and 5.5 were deposited during a single

Plate 5.1. The lower member of formation B overlying diamicton of formation A in the central portion of Golden Valley Bluff (near DNP78-13). Note the synformal collapse structure in the sand (arrow), overlain by horizontally bedded undeformed sand. About 9 m of outcrop are shown in this photo.

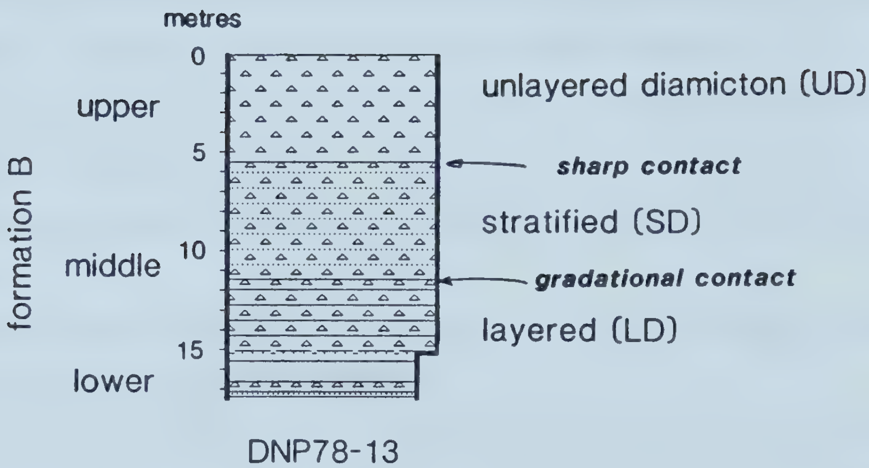


Figure 5.5. Lithofacies sequence with gradational contacts within formation B at Golden Valley Bluff.

glacial advance (Fig. 5.6 a and b). This would have involved:

(i) Formation of lithofacies LD by the molding of subglacial sediment.

(ii) Floating or detachment of the glacier from its bed by undermelting, to allow subglacial deposition of lithofacies SD by raining out and debris-flows.

(iii) Subsequent regrounding of the glacier so that lithofacies UD could be deposited subglacially by melting out and lodgement (Figure 5.6, d).

(iv) Deposition of lithofacies DCL from a supraglacial position during the late stages of melting of inactive ice during glacial retreat.

2. Alternatively the lithofacies sequences depicted in Figure 5.4 and 5.5 could have been deposited during an advance-retreat-readvance event that involved the following:

(i) Formation of lithofacies LD by the molding of subglacial sediment.

(ii) Deposition of lithofacies SD proglacially by raining out from pack-ice and by debris-flows during glacial retreat.

(iii) Subsequent readvance that deposited lithofacies UD subglacially by melting out and lodgement.

(iv) Deposition of lithofacies DCL from a supraglacial position during the late stages of melting of inactive ice during glacial retreat.

The vertical lithofacies sequence shown in Figure 5.4, is internally gradational and therefore must be considered in its entirety to explain the genesis of formation B. Evidence for a glacial origin for the basal part of this sequence (lithofacies LD) include the following:

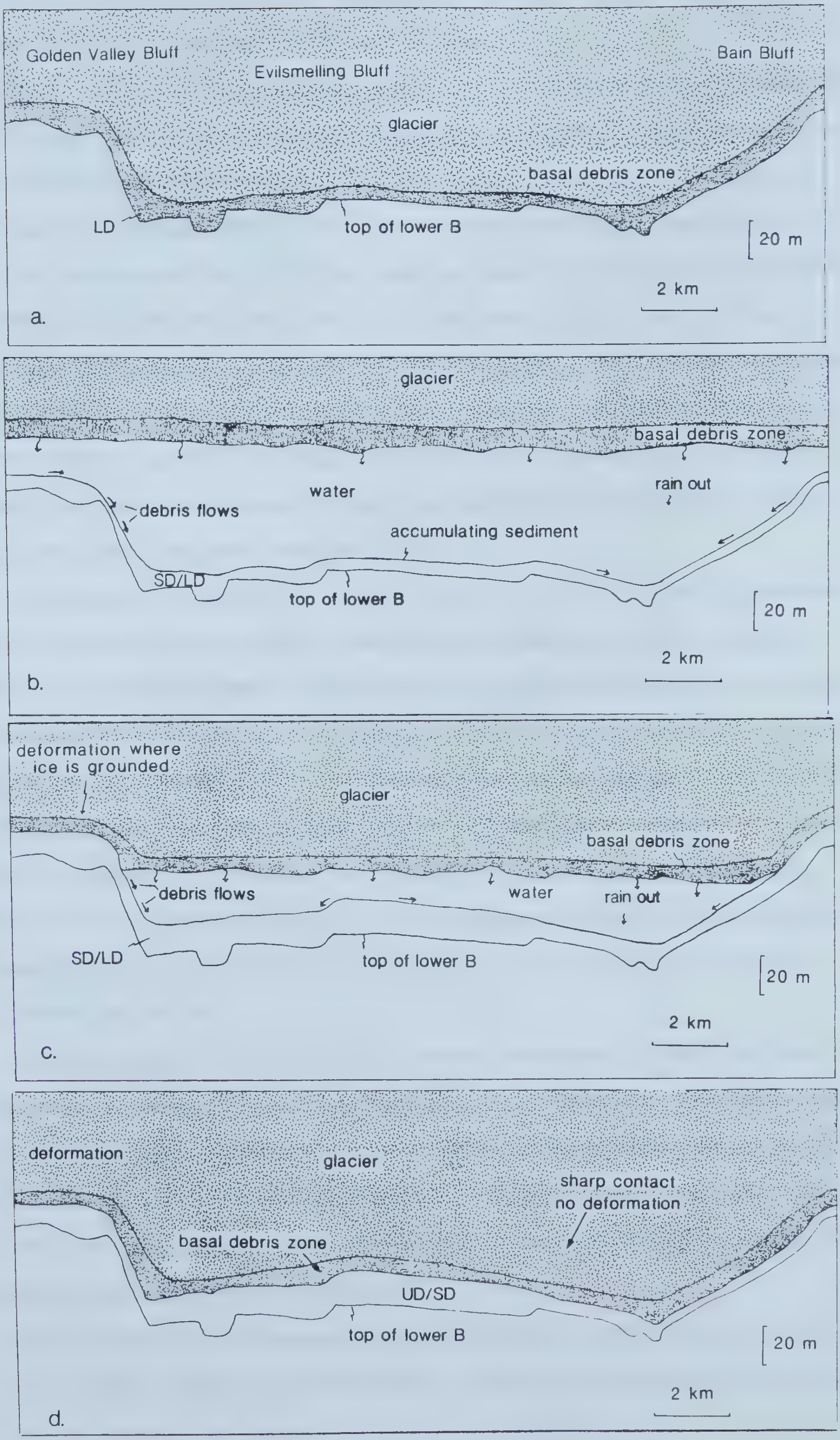
(i) Probable glaciotectonic deformation occurs directly below the middle member of formation B at Evilsmelling Bluff (DNP79-14, unit 1; Plate 2.19), in the lower member of formation B, where the upper 1 to 3 m of sand exhibits drag-style folding.

(ii) The basal contact of lithofacies LD is sharp and is likely erosional.

(iii) Lithofacies LD, which is interpreted to have originated subglacially due to shear, directly overlies this drag-folded sand (discussed in chapter 4).

The preferred orientation of microclasts (Figure 2.7) within lithofacies LD show broad unimodal and bimodal trends (northeast -- southwest and northwest -- southeast) that could represent orientations parallel and transverse to glacial flow (Figure 2.7: d, e, i, j). The northeast -- southwest trend is parallel to the trace of drag-fold axis trends

Figure 5.6. Schematic diagram showing the deposition of the middle and upper members of formation B. a. Glacier occupies the valley, deforming the lower member of formation B (LB), leaving a deposit of lithofacies LD (layered diamicton). b. The glacier floating in a preglacial lake, especially over the valleys where the water is deepest. Deposition of lithofacies SD (stratified diamicton) by rain out and debris flow. c. Lower lake level causes floating ice margin to ground on topographically high areas, leaving only the valley floor ice free. Deformation occurs in these high areas. Rainout and debris flow deposition of SD continues in the valley beneath the ice. d. Ice completely reoccupies the valley and deposits lithofacies UD (unlayered diamicton) by basal meltout.


Golden Valley Bluff
Evilsmelling Bluff
Bain Bluff
glacier
basal debris zone
LD
top of lower B
20 m
2 km
a.
glacier
basal debris zone
water
rain out
debris flows
accumulating sediment
SD/LD
top of lower B
20 m
2 km
b.
deformation where
ice is grounded
glacier
basal debris zone
debris flows
water
rain out
SD/LD
top of lower B
20 m
2 km
c.
deformation
glacier
sharp contact
no deformation
basal debris zone
UD/SD
top of lower B
20 m
2 km
d.

measured in the sand directly below lithofacies LD at Evilsmelling Bluff (Figure 5.7). Therefore, glacial flow was likely from the northwest.

Lithofacies SD conformably overlies lithofacies LD sediments at Evilsmelling Bluff (DNP79-14, unit 3 and DNP79-11, unit 7). This suggests a change in environment from one in which subglacial shear was occurring to one that allowed the accumulation of undeformed stratified diamicton (SD). The lateral extent of this deposit (hundreds of metres) and the absence of any gully-like erosion surfaces or lenses of sorted sediment within lithofacies SD require a large area of accumulation in which there was little or no flowing water. Shreve (1972), Nye (1976) and Rothlisberger (1968) have shown that the prolonged existence of a subglacial cavity is unlikely without abundant flowing water to maintain it. However, a water-filled cavity within the valley in which this sequence was deposited could also be maintained. There is insufficient data to differentiate between a subglacial cavity and a proglacial lake environment.

The absence of evidence for abundant water flow in this sediment suggests that deposition occurred at some distance from subglacial water flow, either between channels or away from the glacier grounding line. It is possible that the upward gradation from lithofacies LD to SD with no intervening ice-marginal washed sediment, as would be expected from a continental glacier, occurred as grounded ice floated off the bottom (Fig. 5.6 b). This could then have allowed debris-flows and raining out to deposit lithofacies SD (discussed in chapter 4). It is possible that sediment was distributed by a floating ice margin or pack-ice (Figs. 4.6 c and Fig. 4.7), with subsequent debris-flows originating from instabilities on the lake floor, and possibly from the ground line of a floating or partially floating ice margin.

In a few localities, lithofacies IDSS-T overlies lithofacies LD (DNP78-4) within the middle member of formation B, or it comprises most of the member. Lithofacies IDSS-T is interpreted to be subaquatic; diamicton beds were deposited by debris-flows, and sand and silt beds by density underflow (see chapter 4). These interbedded deposits (IDSS-T) could have been deposited in or adjacent to subaquatic fans (Fig. 5.8) at the same time that lithofacies SD was being deposited elsewhere.

Nine kilometres to the southwest, testholes GSC69-6 and GSC69-7 (Fig. 3.3) clearly show a fine to medium grained sand that is 7 m thick in GSC69-6 and 18.9 m thick

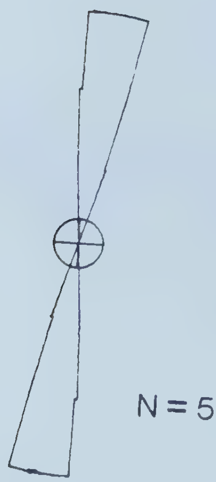


Figure 5.7. Rose diagram (10 degrees moving average) showing the orientation of drag-fold axes in the lower member of formation B at Evilsmelling Bluff (Plate 3.10).

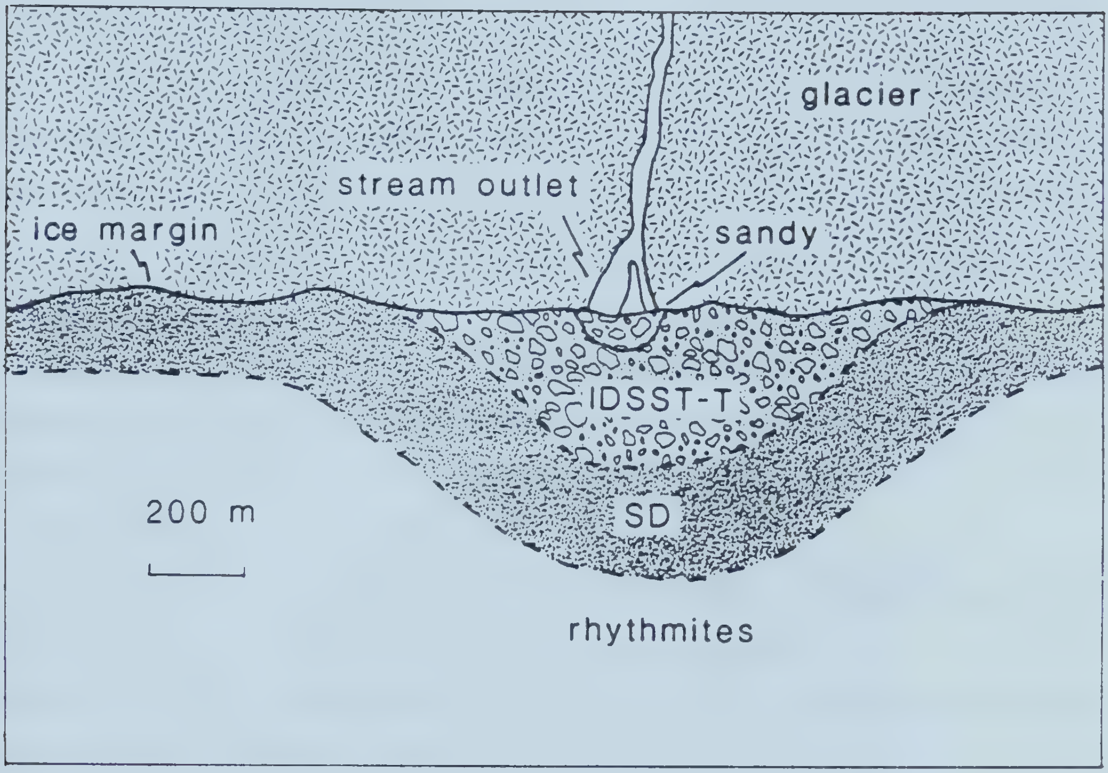


Figure 5.8. Hypothetical plan view of lithofacies distribution during the deposition of the middle member of formation B. IDSS-T (interbedded diamicton, sand, and silt - tabular) is deposited near the stream outlet into the lake either under the floating ice margin or proglacially. SD is deposited farther away from the subaquatic fans, and rhythmites are laid down in the quiescent distal areas of the lake.

in GSC69-7, directly underlying the uppermost formation B diamicton. This sand body is tentatively interpreted to be a lithofacies of a subaquatic fan that was deposited near the entrance of a channel into the subglacial or proglacial lake. This channel could have originated subglacially or from beyond the glacier margin.

Lithofacies UD, in the base of the upper member of formation B, gradationally overlies SD at Evilsmelling Bluff (Figure 5.4). This diamicton is unlayered (lithofacies UD), 2 to 3 m thick, and is interpreted to have been deposited by basal melting out, probably from basally stranded debris-rich ice (see chapter 4). This interpretation is based on the following:

1. Its basal position within the upper member of formation B, and the fact that it lies directly on a sharp basal contact in most places.
2. The absence of primary structures, including stratification.
3. Its thick bedded individual occurrence.
4. Its lateral continuity over hundreds and probably thousands of metres (it occurs in every outcrop of the upper member of formation B in the study area).
5. The occurrence of drag-style deformation folds directly beneath the basal contact at Golden Valley Bluff (Plates 2.1 and 2.2).

The gradational contact between lithofacies SD and UD, shown in Figure 5.4, could be the result of local regrounding of the floating glacier margin, with little or no subsequent ice flow to disrupt lithofacies SD. Lithofacies UD then melted out of the debris-rich basal ice. Figure 5.8 shows the distribution of lithofacies along the ice margin or along the grounding line of a floating ice margin.

Deformation directly beneath the unlayered diamicton (UD) of the upper member of formation B along the central and southern parts of Golden Valley Bluff is likely glaciotectonic, and provides further evidence for a subglacial origin for the base of this member. Large-scale recumbent folds occur in the middle member of formation B, just below the sharp basal contact of the upper member of formation B (Plates 1.1, 2.1 and 2.2). It is likely that this deformation occurred subsequent to the deposition of the middle member of formation B, since it includes the entire unit. Unfortunately, these parts of the outcrop are inaccessible, so that discussion is based on an examination of the outcrop through binoculars. These fold structures are difficult to explain by density loading,

because they are directional structures. Their true orientation is unknown; however, they could have formed as the result of mass movement to the south. This style of deformation was discussed by Boulton (1970a) and Berthelsen (1979) and is attributed to subglacial shear.

About 150 m to the north of these large structures, there is an horizontal zone within the middle member of formation B that extends for about 50 m northwards and contains *en echelon* bed segments of silty sand. These light gray, tabular blocks range in size from 1 to 2 m long, by 10 to 30 cm thick, are separated by 0.5 to 2 m of dark gray diamicton, and are oriented so that they dip towards the north (about 315° to 045°, estimated from two dimensions), at an angle of between 30° and 60°. Unfortunately, this part of the outcrop is also inaccessible and has only been studied through binoculars. However, these structures could have formed when the middle member of formation B was deformed by southerly moving ice.

The lateral change in the nature of the contact at the base of the upper member of formation B from sharp and planar at Golden Valley Bluff (Figure 5.5 and Plate 2.9) to gradational at Evilsmelling Bluff (Figure 5.4 and Plate 3.10) requires some explanation. Lithofacies SD could have been deposited beneath a floating or partially floating (undermelted) ice margin (Fig. 5.6, b-c), with subsequent regrounding of the then stationary glacier (Figure 5.6 d). This might have occurred during a progressive lowering of the proglacial lake level or by reattachment of the undermelted glacier bed. The elevation of the base of the upper member of formation B at Golden Valley Bluff is more than 30 m higher than at Evilsmelling Bluff (refer to Fig. 3.1). Therefore, ice flow could have affected the sediment in the higher area before it was low enough to ground elsewhere. If this part of the glacier stopped advancing during this time, then no deformation would have occurred in the lower area.

Alternatively, the lithofacies association within the middle and upper members of formation B could have formed during two separate advances or during an advance, a retreat, and a readvance. Lithofacies LD would be deposited subglacially by active ice that deformed existing basal sediment, as was suggested in the previous hypothesis. Lithofacies SD was deposited proglacially during glacial retreat by subaquatic debris-flows (refer to chapter 4). Lithofacies IDSS-T sediments were probably deposited in association

with subaquatic fans in this proglacial lake. Subsequently, a glacial readvance deformed previously deposited sediment of the middle member of formation B, eroded a sharp basal contact and deposited lithofacies UD subglacially along it. Where there is an upwards gradation from lithofacies SD to UD sediments, with no deformation, the preservation of the underlying sediment likely occurred due to a reduction in effective stress along the glacier bed. This could have happened where pore-water pressures in the SD substrate were high. No lateral differences in texture or structure that might affect permeability were observed between sites where the SD-UD contact is gradational and where it is sharp.

Evidence for the duration of the hiatus in glacial sedimentation that could have occurred between the deposition of lithofacies LD and UD is limited to the physical differences in sediment discussed above. Therefore, if this break occurred, it was probably of relatively short duration and was dominated by the subaquatic environment of a proglacial lake.

Phase Two Deglaciation

Evidence for glacial retreat is represented by lithofacies DCL (diamicton containing lenses, Fig. 5.4), which is interpreted to have been deposited supraglacially in a melt-out sediment complex that was ultimately deposited by letting down as underlying debris-rich ice melted (detailed discussion in chapter 4). Many complete exposures of the upper member of formation B contain 1 to 3 m of lithofacies DCL gradationally overlying lithofacies UD. This is particularly evident at Evilsmelling Bluff, where lithofacies DCL is up to 7 m thick, and contains large collapsed sand lenses.

As discussed in chapter 4, lithofacies DCL is interpreted to be supraglacially deposited. This is based on the presence of lenses that could not have survived subglacial shear and the abundant collapse structures. It is likely that lake levels had dropped to below this elevation before deposition occurred, since there is no evidence of lacustrine sedimentation within the upper member of formation B.

At numerous locations along Evilsmelling and Golden Valley Bluffs, lithofacies DCL is gradationally overlain by interbedded silt and clay deposits of formation C. These relatively local, undeformed deposits typically occupy depressions in the top of formation

B diamicton. They are thought to be proglacial or supraglacial lake and pond sediments laid down during the final stages of glacial retreat from the area. Elsewhere, cross-bedded fine to medium sand that has a sharp basal contact with the top of formation B and infills depressions (Plate 3.15) is interpreted to have been deposited in small gullies that formed during final deglaciation.

Airphotograph interpretation and surficial geology maps (Berg and McPherson, 1972) show discontinuous lake sediment cover that is dissected by the present South Saskatchewan River Valley in this area. Wind erosion, which is concentrated along cliff faces in this river valley, has caused the the cliff tops to recede, and has covered them with very fine sand and silt that commonly contains paleosols (Plate 3.15), leaving lacustrine sediment exposures only in protected depressions in the surface of formation B.

Finally, the occurrence of lenticular, interbedded sand, silt, and diamicton (lithofacies IDSS-L) within formation C is confined to gullies that have been cut into the underlying sequence. These deposits have an alluvial fan morphology and are currently accreting. They are clearly post-glacial deposits, but no data were collected regarding their chronology or genesis, because these sediments were beyond the objectives of this research.

VI. QUATERNARY GEOLOGICAL HISTORY AND CHRONOLOGY

The following section provides an interpretation of the geological history of the Quaternary deposits found in the Medicine Hat area. First of all, a mainly genetic history is presented, with very little chronological data, because little dateable material was found during this study. The radiocarbon data for samples collected by Stalker (1969a, 1970, 1972, 1976a, 1977b); Stalker and Churcher (1970, 1972); Szabo, Stalker and Churcher (1973); and Westgate (1968); are then discussed and where possible fitted into the stratigraphy. Refer to Table 6.1 for a stratigraphic and chronological summary.

A. QUATERNARY GEOLOGICAL HISTORY

Preglacial Time

The oldest presumed Pleistocene event was fluvial, as indicated by the gravel that composes the lower member of the Empress Formation. This deposit contains no material derived from the Canadian Shield and is therefore interpreted to be preglacial (Whittaker and Christiansen, 1972). The river that deposited this sediment created and occupied a deep and broad valley. Its predominantly quartzite pebble component is not local and probably was derived from the Rocky Mountains to the west, where Precambrian quartzite abounds (Alley, 1972). There is no evidence of a glacial origin for this member.

The base of the middle member of the Empress Formation is marked by a sharp contact that is interpreted to be a depositional hiatus. It is overlain by a cross-bedded sand unit that is up to 12.4 m thick and is thought to be fluvial sediment. This river also deposited interbedded sand, silt, and clayey silt sediment that is interpreted to have been laid down as a fluvial overbank deposit. During this time, vegetation flourished on the floodplain, as evidenced by a small stump found in growth position and by abundant wood fragments found in the cross-bedded sandy lithofacies.

Phase One Glaciation

The upper member of the Empress Formation and formation A are interpreted to represent a complete sequence of sediments deposited by a single glacial advance and retreat. First of all, a fining upwards sequence of thick-bedded silts capped by

ROCK STRATIGRAPHY		LITHOLOGY	EVENT STRATIGRAPHY
FORMATION C		silt and clay rhythmites; massive silt containing paleosols; interbedded sand, silt and diamicton	Post Glacial
FORMATION B	upper member	diamicton	PHASE TWO Glacial
	middle member	sand, silt and diamicton	
	lower member	sand and gravel (wood)	Inter- stadial / glacial?
FORMATION A		diamicton	PHASE ONE Glacial Advance / Retreat?
EMPRESS FORMATION	upper member	silt and clay	Fluvial (Preglacial)
	middle member	sand, silt and clay (wood)	
	lower member	sand and gravel	
BEDROCK		sandstone, siltstone, shale, ironstone and coal	

Table 6.1. Summary of rock and event stratigraphy and lithology for the Medicine Hat area

rhythmically bedded silt and clay, were deposited gradationally over the cross-bedded sandy lithofacies. It was deposited in a proglacial lake that formed when regional drainage was dammed by the glacial advance. The major source for the water and sediment that entered this lake basin was likely nonglacial, derived from the regional drainage system to the west, since there is a complete absence of material derived from the Canadian Shield in all but the uppermost part of this unit.

Glacial overriding of the area is marked by an erosional unconformity at the top of the silt-clay rhythmites of the upper member of the Empress Formation. Subsequent deposition of unlayered diamicton (lithofacies UD), belonging to formation A, occurred subglacially along this sharp contact. This was followed by a succession of supra- and proglacially deposited, interbedded diamicton, sand, and silt (facies IDSS-T).

Interglacial / Interstadial

An interglacial or interstadial period followed the deposition of formation A. In most places, it is marked by a lag gravel that is interpreted to be an erosional unconformity and by fluvial sand and silt that occupies the bottom of the interglacial valleys that are incised into or through formation A (e.g. north end of Golden Valley Bluff, Plate 3.1 and Fig. 3.3). Wood has been found in place within this unit, and the dates obtained by other researchers are discussed below (see chronology).

Phase Two Glaciation

The lower fluvial member of formation B is gradationally overlain by the middle member, which is a fining upwards sequence of sand and silt. It is interpreted to have been deposited in the more distal parts of a proglacial lake that formed when approaching ice again dammed regional drainage. This relatively quiescent-water sediment is overlain by subglacially deposited sediment (lithofacies LD) that grades upwards into stratified diamicton (lithofacies SD) of the middle member of formation B. Therefore, this glacier must have overridden the area, deforming the lower member of formation B and depositing lithofacies LD.

Subsequent to the deposition of LD, the margin of this glacier could have floated off of its bed to allow deposition of lithofacies SD by rain out and debris-flow (discussed in chapter

4). This assumes that the ice margin was in the vicinity at the time. In addition, lithofacies IDSS-T sediments could have been deposited adjacent to subglacial stream outlets into the lake (Fig. 5.7). Later, they may have again come into contact with the floating glacier margin as it regrounded. Lithofacies UD could then have been deposited subglacially by melt out.

Alternatively, this glacier could have retreated from the area leaving a proglacial lake in which SD was deposited. The sediment sequence found within the upper member (UD overlain by (DCL) and the rhythmically bedded sediment at the base of formation C is then interpreted to represent a complete sequence for a single glacial advance and retreat cycle. The deformation in the middle member of formation B and the sharp erosional basal contact of the upper member likely formed during glacial advance. Later, unlayered diamicton (lithofacies UD) was deposited subglacially.

During glacial recession, diamicton containing lenses (DCL) of supraglacial origin was lowered to the ground surface by basal melting.

Phase Two Deglaciation

As the ice melted, a proglacial lake must have covered its last remnants. During this time, and continuing on after all ice had melted, a thin deposit of silt and clay (less than 2 m) was laid down. The meagre thickness of these lacustrine deposits suggests that only a small volume was deposited, from which it is inferred that this phase of the lake was relatively short-lived.

After the lake had emptied, regional drainage was re-established, probably following a topographic depression that was situated locally over the preglacial river valley. Aeolian erosion of cliff faces and deposition in cliff-top dunes accompanied the downcutting of the present river valley.

B. QUATERNARY CHRONOLOGY

The chronology of the Quaternary sequence preserved in the Medicine Hat area is based on radiocarbon dates for material collected by Stalker (1963b, 1969a, 1970, 1972, 1976a, 1978, 1983), Stalker and Churcher (1970, 1972, 1982), and Westgate (1968). No new dateable material was found during the course of this study, except in

beds adequately dated previously. However, nine wood samples were analyzed for amino acid ratios. These data are presented in Table 6.2. Unfortunately, there is no experience with racemization rates and no paleotemperature curves for this region (N. W. Rutter, University of Alberta, personal communication, 1983). A comparison of amino acid ratios from the same stratigraphic horizons, for relative dating, is not possible here because of the small number of sample analyses available. Table 6.3 provides a summary of the dates within the stratigraphy delineated during this project. These data were not used in the development of the physical stratigraphic framework, but were subsequently fitted into it. The fitting of this data into the physical stratigraphic framework developed in this study is based on the author's knowledge of the respective sections and a detailed review of all pertinent literature and discussions with A. Macs. Stalker.

This interpretation of the radiocarbon data indicates that there are three dated horizons.

1. Proglacial sediment of the middle member of the Empress Formation are older than 46,700 years B.P. (GSC 543, Lowden *et al.*, 1967; from the south end of Golden Valley Bluff). All dates in this interval are infinite.

2. Interglacial sediments of the lower member of formation B are in the range of 24,490 (GSC 205, Dyck *et al*, 1965) to 28,630 (GSC 578, Lowden *et al.*, 1967).

3. Postglacial sediments of formation C are at least 11,200 years old (GSC 805, Lowden and Blake, 1968) and provide a minimum date for deglaciation.

No attempt is made to discuss the vertebrate paleontological chronology developed by C.S. Churcher (Stalker and Churcher, 1970, 1972, 1982) for the older parts of the sequence that are beyond the range of radiocarbon dating.

Univ. of Alberta Lab no.	Location	Sample description	Formation	Aspartic	Glutonic	Leucine	Proline
1211	Evilsmelling Bluff (DNP81-2B)	wood fragments in diamicton (colluvium, not mineralized)	lower member B	0.081	0.069	0.012	-
1210	Evilsmelling Bluff (DNP81-2A)	"	"	0.084	0.109	0.014	-
941	Evilsmelling Bluff (DNP81-3)	wood fragments in diamicton (colluvium?)		0.163	0.115	0.039	0.042
942	Island Bluff (east) (DNP78-4)	20 cm diameter log within diamicton	A	0.064 0.069	0.035 0.035	0.011 0.014	- -
940	Mitchell Bluff (east)	wood fragments in sand	middle Empress	0.116 0.121	0.09 0.101	0.018 0.018	- -
944	"	wood twigs or roots in clay lens within sand	"	0.282	0.117	0.145	0.072
943	Golden Valley Bluff (south end, DNP81-7)	"	"	0.412	0.244	0.101	0.122
939	Golden Valley Bluff (north end, DNP79-16)	intact 7.5 cm stump in growth position in sandy silt	middle Empress	0.229	0.153	0.049	0.100
				0.192	0.106	0.029	0.013

Table 6.2. Amino acid ratios for wood found in sections near Medicine Hat.

Lithostratigraphic Unit	* Radiocarbon Date	Material	Reference Number	Location
formation C	1,110 ± 140	charcoal	GSC 1302	Bain Bluff
	5,540 ± 250	bone	GSC 802	Bain Bluff
	8,120 ± 170	shell	GSC 1341	Bain Bluff
	10,200 ± 240	shell	GSC 1061	Bain Bluff
	11,200 ± 200	bone	GSC 805	Lindoe Bluff
Lower member of formation B	24,490 ± 200	plant fragments	GSC 205	Evilsmelling Bluff
	25,000 ± 800	wood fragments	GSC 1370	Evilsmelling Bluff
	28,630 ± 800	poorly preserved wood fragments	GSC 578	Evilsmelling Bluff
?	37,900 + 1,100	wood	GSC 144-2	Galt Island Bluff
Empress?	29,200 + 8,100 - 4,000	carbonized wood	GX 102	north end of Golden Valley Bluff
	36,600	wood	GX 210	"
	>30,000	wood fragments	GSC 780	Mitchell Bluff
	38,700 ± 1,100	wood	GSC 144-2	Galt Island Bluff
	>36,000	shells	GSC 876	Surprise Bluff
	>36,000	wood	GSC 847	Mitchell Bluff
				Mitchell Bluff
	>38,000	wood	GSC 1044	Mitchell Bluff
	>46,700	wood	GSC 543	Golden Valley Bluff north (Lehr Gulley)

Table 6.3. Summary of radiocarbon dates for the Medicine Hat area Quaternary sequence

GSC (Geological Survey of Canada radiocarbon laboratory)

GX (University of Toronto radiocarbon laboratory)

* All dates are from Jackson and Pawson, 1984.

VII. CONCLUSIONS

This chapter is intended to summarize the progress made towards the objectives of this project and to make some general comments regarding the character of glacial sediments in the Medicine Hat area.

1. A Quaternary lithostratigraphic framework has been developed for the Medicine Hat area. It includes four formations, of which the Empress is preglacial, formation A is glacial, the lower member of formation B is nonglacial, the middle and upper members of formation B are glacial, and formation C is postglacial. Existing radiocarbon data from the sections studied have been used to develop a Quaternary chronology (Table 6.1).
2. Eight diamicton and associated lithofacies (Table 2.2) have been delineated and genetically interpreted, as well as several more widely recognized fluvial and lacustrine lithofacies. These lithofacies have been used to account for unit variation within the stratigraphic framework. Table 5.1 summarizes these lithofacies, with the most likely genetic interpretation for each within the study area.
3. An attempt was made to recognize typical lithofacies sequences. This proved to be impractical given the variety of sequences present, the rare ocurrence of some lithofacies, and the possibility that a given lithofacies can have more than one genesis, depending on its position in the sequence.

   However, unlayered diamicton (lithofacies UD) that is relatively thick and occurs singly, is generally found at the base of a given glacial sediment sequence. Diamicton containing lenses (DCL), occurs mainly at the top of glacially derived sequences.
4. All lithofacies have been interpreted individually using process sedimentology and modern analogs where possible. Each lithofacies has several genetic possibilities that require a detailed examination of individual lithofacies associations to determine its most likely genesis.

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APPENDIX A: SECTION DESCRIPTIONS

Terminology

The terminology used in the description of sections is outlined in chapter 2 (refer in particular to Table 2.2). Where question marks follow a lithofacies abbreviation, the lithofacies classification is uncertain. The slash (/) is used with lithofacies abbreviations to indicate that one lithofacies overlies another (eg. LD / UD). The unit numbers listed for each section are section specific, indicating the sequence in the outcrop and do not refer to the nomenclature used in the paper. These unit numbers are referred to in the text. Location coordinates for each section are given in the Dominion Land Survey System. Sections can be located on Figures 1.2 and 2.2 using the name of the section for a general location and the index number for specific sites.

Bain Bluff

1. Bain Bluff Centre DNP78 10

Location: On the right bank of the South Saskatchewan River in a small gully that cuts the upper slump scarp.
NE4-1-14-5-W4

Elevation at the top of the section: 762 m (2500 ft)

Comments: This is one of the deepest exposures at this section.

7. Silty sand: horizontally bedded; beds are 5 - 30 cm thick with three poorly developed dark brown paleosols 3 to 10 cm apart; contains few pebbles; lower contact obscurred; unit is 1.8 m thick.

6. Diamicton: silty, sand; olive brown (2.5Y 4 / 2? moist); large columnar structure (1 x 2 m x thickness of unit); unbedded; lower contact gradational up close, but very distinct from distance; unit is 3.2 m thick; lithofacies UD?

5. Diamicton: silty, sand; olive brown (2.5Y 4 / 4 moist); has more stones than unit 6, (5 - 10%) with stones up to 20 cm diameter; contains parallel, horizontal beds of silt and sand that vary in thickness from 2 to 10 cm, are topped with dark grey silty clay beds less than 5 mm thick. can be traced across the outcrop for more than 5 m, and are 5 to 30 cm apart. Diamicton breaks into small irregular rounded pieces and appears to be composed of these "balls"; lower contact of unit is gradational, determined on basis of colour change and break in slope; unit is 2.5 m thick; lithofacies SD.

4. Diamicton: clayey, silt; greyish brown (2.5Y 5 / 2 dry); upper 0.5 m contains stratification as in unit 5; has abundant arcuate, near horizontal fractures which commonly intersect and could be shear planes; they contain scratches, oriented at 100° - 280° (caused by slumping into the valley?); lower contact is sharp and very irregular unit is 2.3 m thick; lithofacies SD?

3. Diamicton: clayey, silt; very dark grey (5Y 3 / 1 dry); contains frequent subparallel 0.5 to 2 cm sand and silty clay stoneless interbeds; sand beds are oxidized brown and contain abundant gypsum; unit is 1.4 m thick, but lateral extent uncertain, may be an inclusion; sharp lower contact; lithofacies SD?

2. Diamicton: clayey, silt; very dark greyish brown (2.5Y 3 / 2 dry); unlayered; sharp basal contact; unit is 1.4 m thick but poorly exposed; lithofacies UD?

1. Sand: medium to fine grained; well sorted; difficult to see structures due to poor exposure, but some graded bedding and cross stratification observed; unit is at least 8.4 m thick and is exposed in gully bottom.

2. Bain Bluff Centre DNP78 9 + 81 14

Location: On the right bank of the South Saskatchewan River in the largest gully cutting the upper slump scarp. It has large trees at its base and overlooks a small lake in the slump blocks.
NE13-36-13-5-W4

Elevation of the top of the section: 762 m (2500 ft)

Comments: This is the best exposure at this section but only the upper 25% of the material above river level is exposed. Measured along the wall of the gully.

6. Silt and very fine sand: horizontally bedded; beds are 5 - 30 cm thick; at least three dark brown paleosols occur near the top of the unit with an ash bed 1.5 m from top; columnar jointed; lower contact sharp; unit is 2 m thick.
* Note: 50 m to the north a small gully exposes interbedded fine sand and silt beds 20 - 50 cm thick, with some thin gravelly interbeds. Unit is 5 m thick and occurs in a depression in top of unit 5 and is overlain by unit 6.

5. Diamicton: silty, sand; olive brown (2.5Y 4 / 4 moist); unlayered; large columnar structure (1 x 2 m x thickness of unit); forms steep cliff face, no sand lenses; sharp wavy lower contact; unit is 6.6 m thick; lithofacies UD.

4. Diamicton: clayey, silty; dark greyish brown (2.5Y 4 / 2 moist); contains subparallel discontinuous layers less than 2 cm thick of sand and gravel, with elongate and flat pebbles lying parallel to the layering; these layers are from 2 - 50 cm apart and die out laterally; diamicton has a noticeably higher proportion of 2 - 4 mm fraction, has strong columnar jointing (5 x 2 x 2 cm) with little or no joint staining; sharp lower contact. Unit is 6.4 m thick; lithofacies LD.

3. Gravel: sandy with clay; clasts up to 15 cm in diameter; no sand lenses; very disorganized unsorted appearance, unbedded; some rocks are heavily fractured, some are oriented vertically; bone fragments found near top of unit; upper 60 cm is finer grained, but has no stratification; lower contact is gradational; unit is 3.8 m thick.

2. Sandy Gravel: medium sand to clasts 5 cm in diameter; well sorted with horizontal, horizontally bedded gravel interbedded with sand beds (less than 2 cm thick) and some silty clayey diamicton beds; see blow-up of a portion of unit 2 (Plate 3.11); no cross-bedding; exposure is approximately 6 m wide, lower contact is sharp; unit is 1.8 m thick.

1. Diamicton: silty clay; olive brown (2.5Y 4 / 2 dry) or very dark grey (10YR - 3 / 1 moist); small columnar jointing (4 x 2 x 2 cm); abundant granules; no stain; this is a very small exposure (about 1 m^2); unit is less than 1 m thick; lithifacies undifferentiated.

Mitchell Bluff

3. Mitchell Bluff East DNP80 53 and 53A

Location: Right bank of South Saskatchewan River at east end of Mitchell Bluff East, approximately 100 m west of the irrigation pump house.
SE16-33-13-5-W4

Elevation of the top of the section: 686 m (2250 ft)

Comments: This description is representative of approximatley 30 m of section laterally.

12. Silt: pale yellow (2.5Y 7/4 dry); unbedded; columnar jointed; sharp lower contact; 1.0 m thick.

11. Gravel: pebble to cobbles; 1 to several clasts thick (<10 cm); forms lenses in top of unit 10.

10. Diamicton: silty, sand; light olive grey (5Y 6/2 dry); unlayered; forms steep cliff face that is obscured by a thin coating of slopewash silt; exposed face has rectangular cracks that do not penetrate into the cliff face; lower contact is sharp; 6.1 m thick; lithofacies UD?

9. Sandy silt: block or bed of poorly exposed fine sandy silt; upper 0.5 m deformed; sharp lower contact; unit thickness is irregular, up to 1 m.

8. Diamicton: clayey, silt; light olive grey (5Y 6/2 dry); to dark greyish brown (10YR - 3.5/2 wet); blocky structure (3 cm^3); brownish yellow joint staining (10YR - 6/6 dry); upper 50 cm contains many sand and silt lenses that are internally deformed; lower contact sharp; unit is 1 m thick; lithofacies DSD?

7. Sand: bottom 15 cm of unit is coarse sand, grading up through cross-bedded fine to medium sand to a silt bed 20 cm thick that is 1.4 m from top of the unit; above it is horizontally bedded fine sand with minor 1-2 cm silty clay beds; sand and clay rip-up clasts occur near the top; bedding planes are marked by coal fragments and rust stain; a few small red-orange bone fragments occur in this unit; lower contact largely covered - may be gradational. Unit is 4.2 m thick.

6. Gravel: fining upwards from 0.3-0.8 m cobbles at the base to 0.5 cm diameter clasts at the top; sandy matrix throughout; contains granites; unit is 60 cm thick.

5. Diamicton: silty, clay; olive grey to greyish brown (5Y 5.5/2 dry); unlayered; blocky to fractured structure; dark reddish brown (2.5Y 3/3 dry) stain on fracture faces; lower contact is sharp with scratches at 067 and 085^0; unit is 30 cm thick here, but laterally ranges from 50 cm to being entirely missing where unit 6 has been eroded through; lithofacies UD.

4. Silt: laminated, with rare thin clay beds; columnar jointed; lower contact covered; unit is about 4.8 m thick.

3. Silt, Sand and Gravel: coarse, with rocks up to 15 cm in diameter; includes clasts of granite and a diamicton boulder 50 cm in diameter; ; silt is horizontally discontinously bedded, with thin gravel lenses; coarse gravel at base; unit is irregular in thickness (0.2 to 1 m) along approximately 20 m of section forming a convex outline with gravel beds rising up almost to the base of unit 5.

2. Sand: medium to fine grained; well sorted; largely tabular cross-bedded with scours up to 1 m deep; some horizontally bedded sand and a few silt beds; coal fragment concentrations and clay rip-up clasts occur in places particularly in trough cross-beds; wood/root segments found intact in places as buried detritus in sand and silty clay beds; wood in sand heavily mineralized; but much like charcoal in silty clay beds; lower contact gradational; unit thickness is 7 m.

1. Clayey silt and sandy silt: dark blue grey colour, unoxidized; even parallel bedded; interbedding of clayey silt and sandy silt beds averaging 5 to 10 cm thick; gradational upper contact; unit is greater than 5.4 m thick; base is below level of South Saskatchewan River.

4. Mitchell Bluff Centre DNP78 8

Location: On right bank of the South Saskatchewan River at top of the slump scarp (see Figure???)
SE-10-33-13-5-W4

Elevation of the top of the section: 693 m (2275 ft)

Comments: This is the best exposure at the uppermost part of the sequence of this section.

5. Diamicton: silty, sand; olive brown (2.5Y 4/4 moist); columnar jointing (1 x 2 x thickness of unit); 3 - 5 % clast content; unlayered; forms steep cliff face; lower contact is sharp, horizontal and smooth, but poorly exposed; lithofacies UD? Unable to examine upper part of unit due to inaccessability. Estimated thickness 8.0 m.

4. Silt, sand and diamicton and gravel: this unit is sketched in Figure 2.8 in detail; gradational lower contact; thickness 8.5 m; lithofacies IDSST-T.

3. Diamicton: clayey, silt; very dark grey (2.5Y 3/2 dry); unlayered blocky diamicton; grades upward into diamicton with minor thin, horizontal (< 3 cm) silt and sand beds in the upper 1.5 m; lower contact is sharp, and emphasized by a break in slope; unit is 2.5 m thick; part of lithofacies IDSS-T.

2. Silty sand and diamicton: bottom 25 cm is cross-laminated medium to coarse sand topped by a 2 cm discontinuous gravel bed; overlain by an interbedded sequence of 1 - 2 cm thick diamicton beds each of which is overlain by approximately 10 cm of silty sand; lower contact of unit is sharp but little change from unit 1; unit is 1.2 m thick; part of lithofacies IDSS-T.

1. Diamicton: clayey, silt; dark grayish brown (2.5Y 4/2 dry); unlayered; blocky structure; clast content 1 - 3%; contains rare irregular sand lenses and silt lenses or blocks; lower contact covered; unit thickness greater than 8.3 m; lithofacies UD?

5. Mitchell Bluff Centre DNP79 4

Location: On the right bank of the South Saskatchewan River at the top of the slump scarp, approximately 100 m west of the fence which can be seen at the top and base of the cliff; at the west central end of section.
NE6-33-13-5-W4

Elevation of the top of the section: 693 m (2275 ft)

Comments: Site sampled because two diamictons are exposed here.

5. Sand and silt: mapped on basis of scree, no outcrop; approximately 9 m thick. Appears to be a channel cut down from present day surface, since it does not continue laterally at same elevation.

4. Diamicton: clayey, silt; dark greyish brown (2.5Y 4/2 dry); blocky structure (3-4 cm^3); minor sand lenses near base are probably in place since undeformed; stratification near top of unit or just above where contact placed; poorly exposed upper contact; lower contact is sharp; unit is 3 m thick; part of lithofacies IDSS-T.

3. Diamicton: clayey, silt; dark olive (5Y 3/5 dry); small blocky structure (1 cm^3); unlayered; but contains thin irregular sand lenses near the top of the unit; differentiated from unit 4 on basis of color and contact; lower contact gradational; unit is 1.7 m thick; part of lithofacies IDSS-T.

2. Silty Sand and Diamicton: interbedded silty sand beds (10 - 20 cm) thick and diamicton (2 -10 cm); unit pinches and swells laterally; lithofacies IDSS-T; thickness is 0.8 m where measured.

1. Diamicton: clayey, silt; olive (5Y 5/3 dry); unlayered; blocky structure; brownish yellow joint stain (10YR -6/6); limited exposure; unit is > 2 m thick; lithofacies UD.

6. Mitchell Bluff West DNP79 5

Location: On the right bank of the South Saskatchewan River, at top of slump scarp approximately 150 m east of westernmost exposure.
SW12-33-13-5-W4

Elevation of the top of the section: 686 m (2250 ft)

Comments: Lower part of section follows a gully recently cut through formation A or the middle member of formation B, that is the only place where this sequence is exposed.

5. Sandy silt: unbedded; unit is approximately 0.5 m thick.

4. Diamicton: clayey, silt; very dark grey (2.5Y 3/2 dry); inaccessible, but appears structureless; unit is approximately 2 m thick; lithofacies undifferentiated.

3. Sand: fine to medium grained; cross-bedded with beds averaging 40 cm; contains rare lenses of diamicton that resemble unit 2; sharp lower contact; unit is 2 m thick; lithofacies undifferentiated.

2. Diamicton: silty clay; very dark greyish brown (2.5Y 3/2 dry); fine prismatic structure (1 cm^2 x 5 cm); rusty stain on joint faces; lower contact is sharp; unit is 3.5 m thick.

1. Sand: medium to fine grained; consists of cross-bedded and cross-laminated beds; minor gravel lens 13 m below unit 2; poorly exposed. unit thickness is greater than 10 m, with base of exposure approximately 8 m above high stage river level.

Island Bluff

7. Island Bluff South East DNP79 6

Location: On the left bank of the south Saskatchewan River at the southernmost end of the bluff.
SW5-4-14-5-W4

Elevation of top of section: 693 m (2275 ft)

Comments: This is an excellent exposure of the lower part of this section and it overlaps with base of DNP78-4.

2. Diamicton: clayey, silty; olive (5Y 4 / 3 dry); moderate blocky structure (1-2 cm^3); yellowish brown (10YR -6 / 8 dry) joint face stain; unlayered; upper 2 - 3 m contains silt lenses or beds up to 1 to 2 m thick (occurs about 25 m to the north along the outcrop); in places silt layers are rust-stained and have deformed white carbonate lenses or nodules associated with them; lower contact is sharp, with deformation along it; top of unit is truncated by present day erosion; unit is > 6 m thick; lithofacies LD? / UD.

1. Sand: medium to fine grained; oxidized; planar and cross-bedded with minor lenses of silt; clay balls, probably rip-up clasts, occur in upper 1 to 2 m; upper 2-3 m is deformed, with kink folds and micro faults; about 4 m exposed, base of unit is covered.

8. Island Bluff Southeast DNP78 4 and 4A

Location: At the southeast (downriver) end of a large slump scarp on the left bank of the South Saskatchewan River.
NW5-4-14-5-W4

Elevation of the top of the station: 709 m (2325 ft)

Comments: Section measured from the southeasternmost high point on the slump scarp following along the top of the scree slope.

13. Silt and Very Fine Sand: horizontally bedded, beds are 1 to 30 cm thick; at least three dark brown paleosols occur near the top of the unit; weak columnar structure; easily eroded by wind; occurs approximately 8 m back from cliff top; unit is 2 to 3 m thick.

12. Diamicton: silty, sand; light olive brown (2.5Y 5 / 4 dry); oxidized; large columnar joints extend through entire unit; (1 to 3 m apart); bottom 1 m contains rare small sand lenses; upper 2 m contains two 10 cm thick massive undeformed clayey, silt beds, one at 1.2 m and the other at 1.6 m from the top of the unit; near the base of the unit, in the basal 1.5 m, two weak, slightly recessive, stone concentrations occur (intermittent clast alignments), each marked by a stone about every 8 m laterally along the cliff face; no detectable change in the diamicton across these horizons; lower contact is sharp and horizontal, unit is 7.6 m thick; lithofacies DCL? / UD.

11. Silty sand; pale yellow (2.5Y 7 / 4 dry); basal portion is weak, horizontally laminated, very fine sand and silt; upper 20 cm is cross-laminated coarse to very fine sand; pebbles occur rarely; lower contact is sharp, and undulating, with load structures along it; unit is 2.8 m thick; part of lithofacies IDSS-T.

10. Diamicton: clayey, silt; grayish brown (2.5Y 5 / 4dry); blocky structure (2 to 3 cm^3 blocks); unlayered; difficult to trace laterally for more than 20 m due to covered area; may pinch out or thin substantially laterally; very similar in appearance to unit 8; unit has a sharp, wavy lower contact (load structures along it?); locally unit has a consistent thickness of 70 cm; part of lithofacies IDSS-T.

9. Sandy silt: medium sand to silt texture; pale yellow (2.5Y 7 / 4 dry); weakly bedded; a 3 cm light gray (2.5Y 7 / 0 dry) silt zone occurs along the base; basal contact appears loaded; unit is 1.5 m thick; part of lithofacies IDSS-T.

8. Diamicton: clayey, silt; grayish brown (2.5Y 5 / 2 dry); unoxidized; blocky structure (2 to 3 cm^3); brownish yellow (10YR 6 / 6 dry) joint face stain; contains thin discontinuous sand beds (less than 2 cm thick) that are relatively undeformed in outline and have no internal bedding or structure; lower contact of unit is sharp, wavy, poorly exposed; has a higher cobble content than other diamicton units at this station; unit may not be continuous as it cannot be seen in cliff face 75 m to north; unit is 1.5 m thick; part of lithofacies IDSS-T.

7. Sand: medium to fine grained; pale yellow (2.5Y 7 / 4 dry); base of unit is very fine sand and silt that coarsens upwards towards the centre of the unit where small lenses of medium sand occur, it then fines upwards to silt in the top 15 cm; contains few stones, especially along base; lower contact is sharp; unit is 45 cm thick, but varies in thickness laterally ± 25 cm; part of lithofacies IDSS-T.

6. Diamicton: clayey silt; olive brown (2.5Y 4 / 4 dry); weak blocky structure (3-4 cm^3 blocks); strong brown (7.5YR - 5 / 6 dry) to yellowish red (5YR - 5 / 6 dry) joint face stain; upper 40 cm is oxidized; contains few horizontal, undeformed, discontinuous sand beds that have no internal structure, but have sharp uneven contacts with the diamicton; lower unit contact is subtle; unit thickness is 3.1 m; part of lithofacies IDSS-T.

5. Diamicton: clayey, silt; olive brown (2.5Y 4 / 4 dry); blocky (3 cm^3) to prismatic (4 cm x 1 cm^2) structure; dark reddish brown (5YR - 3 / 3 dry) joint stain; lower contact is sharp, irregular; contains horizontal, structureless sand beds that have sharp contacts with the diamicton. One sand lense approximately 35 cm above the base of the unit and 3-5 cm thick, with no internal primary structure, is deformed, with very small diamicton stringers within it; sand stringers extend from the lens into the surrounding diamicton; boulders up to 40 cm in diameter occur near the base of the unit; unit is 2.4 m thick; lithofacies LD?

4. Sandy Gravel: medium to coarse sand with pebbles up tp 4 cm in diameter; pebbles are subangular to subrounded, average 1 cm; distinctive pinkish colour on weathered surface; rust-coloured on fresh surface; contains Canadian Shield rocks; some pebbles have a bright yellow crust on them; lower contact is sharp; unit is 5 - 10 cm thick, contains cobbles near-by; and can be traced for more than 100 m laterally; no primary bedding structures were observed.

3. Sandy Silt: light grey (2.5Y 7 / 2 dry); to pale yellow (2.5Y 7 / 4 dry); finely laminated; some laminae show weak deformation; in places there is a 1 cm thick clay bed along the top of the unit and in places clay lenses 10 - 15 cm thick occur below the silt; unit is discontinuous but is 70 cm thick where measured and can be traced laterally for more than

100 m; lower contact is sharp; unit is heavily deformed laterally, with clay lenses exhibiting faulting and over folding.

2. Diamicton: silty, clay; pale olive (5Y 6/3 dry); strong blocky structure (1-2 cm^3); dusky red joint face stain (2.5YR - 3/2 dry); forms steep cliff and is very inaccessible; lower contact is sharp, horizontal and has deformed sand and clay beds laterally along the contact; no difference observed between units 1 and 2; unit is of variable thickness, but is 8.9 m thick at this station; wood sample 50 cm long and 20 cm diameter found 3.6 m below top of this unit; scratches found on polished basal contact; lithofacies UD?

1. Diamicton: silty, clay; dark greyish brown (2.5Y 4/2 dry); blocky structure (1 - 2 cm^3); dusky red (2.5YR - 3/2 dry) joint face stain; contains thin horizontal deformed cross-laminated sand lenses that are commonly < 2 cm thick, in the upper 3 m of the unit; unit contains very few large clasts; basal contact is covered; thickness is greater than 3.3 m but varies greatly laterally; lithofacies LD/UD?

9. Island Bluff Centre DNP78 7

Location: On left bank of the South Saskatchewan River in a small gully cut into the top of the upper slump scarp.
NE9-5-14-5-W4

Elevation of the top of station: 716 m (2350 ft)

Comments: Good exposure of upper part of the sequence at this section.

5. Diamicton: silt, sandy; light brownish grey (2.5Y 6/2 dry); large columnar structure (1 x 2 x thickness of unit); unlayered?; sharp lower contact; forms vertical cliff but poorly exposed due to surface silt crust; estimated thickness 6 m; lithofacies undifferentiated.

4. Sandy silt: unbedded; poorly exposed; 15 cm thick.

3. Diamicton: clayey, silty; light yellowish brown (2.54 -6/4 dry); blocky structure; 75 cm thick; (poorly exposed), lower contact sharp; lithofacies undifferentiated.

2. Sand: silt to medium sand; poorly sorted; in places, fine to medium sand beds with gradational contacts occur; lower contact sharp; 3.3 m thick.

1. Diamicton : clayey silty; very poorly exposed; difficult to differentiate from slump; > 4 m thick; undifferentiated lithofacies.

10. Island Bluff West DNP81 17

Location: On the left bank of the South Saskatchewan River approximately 250 m east of the west end of westernmost slump scarp.
NW4-5-14-5-W4

Elevation of the top of the station: 709 m (2325 ft)

Comments: Section shows sand between upper two diamictons; a very narrow exposure.

7. Diamicton: silty, sand; light yellowish brown (2.5Y 6 / 4 dry); large columnar jointed (1 x 2 m x thickness of unit); recessive, poorly exposed; lower contact sharp; 4.1 m thick, upper contact eroded by present ground surface; lithofacies undifferentiated.

6. Sand: fine to coarse grained; oxidized; pale yellow (2.5Y 7 / 4 dry); cross-bedded; beds approximately 20 cm thick; unit is 1 m thick.

5. Sand: very fine to fine grained; pale yellow (2.5Y 7 / 4 dry); oxidized; horizontally laminated; sharp lower contact? ; 50 cm thick.

4. Diamicton: grayish brown (2.5Y 5 / 4 dry) ; layered? ; moderate blocky structure (2 cm^3); sharp lower contact; 40 cm thick; unit is poorly exposed; lithofacies undifferentiated.

3. Sand: fine to coarse grained; oxidized; cross-bedded; approximately 50 cm thick.

2. Gravel: sandy with pea to cobble sized clasts; no structures observed, poorly exposed; 60 cm thick.

1. Diamicton: clayey, silty; greyish brown (2.5Y 5 / 4 dry); unlayered; blocky structure (2-3 cm^3); dark reddish brown (5YR-3 / 3 dry); joint face staining; poorly exposed; greater than 1.5 m thick; lithofacies UD?

11. Island Bluff West DNP81 15

Location: On the left bank of the south Saskatchewan River on a new slump scarp along the top of the west side of Island Bluff, east of DNP81-15. approximately 70 m east of the westernmost exposure at the bluff.
NE14-5-14-5-W5

Elevation of the station: 709 m (2325 ft)

Comments: Very fresh exposure; particularly good of upper diamicton lithofacies. Station measured along the outcrop from base in west to top in east, over a lateral distance of approx. 15 m.

4. Silt and very fine sand: laminated to thick-bedded, contains at least three paleosols; weak columnar jointing in places; upper surface vegetated, lower contact sharp; unit is 1 to 2.5 m thick along 100 m of exposure.

3. Sand and silt: fine to medium grained sand; yellowish brown; fines upward from thin plane- to cross -laminated medium to fine sand, to thick-bedded silt; sandy portion of unit in many places contains thin discontinous silt beds and laminae; bedding planes are conformable with the sharp undulating lower contact which appears to be eroded into unit 2. (thickness ranges 0 - 2.5 m).

2. Diamiction: silty, sandy; light yellowish brown (2.5Y 6 / 4 dry); oxidized; prominent

large columnar jointing (1 x 2 x 3 m high); entire unit is 7 m thick.
* Described according to lithofacies:

2d. strong platey structure: horizontal fissility; planes are irregular, discontinuous, marked by reddish black (10R - 2.5 / 1 dry) stain; lower contact gradational; approximately 3 m thick; lithofacies LD?

2c.unlayered; breaks irregularly; lower contact gradational; contains 2 small undeformed horizontal gravelly sand lenses (2 x 15 cm), with graded bedding and channel cross-section geometry (Plate 2.8); contact zone contains a thin, deformed, medium grained sand lense < 5 cm thick and 2 m long, with an overturned fold at one end; unit is 2.5 m thick; lithofacies UD.

2b.contains numerous planar, subparallel discontinuous thin layers of medium to fine grained sand laminae averaging 1 mm thick and not exceeding 3 mm; upper unit contact is gradational; 1.5 m thick; lithofacies LD?

2a. Rare cobbles pressed into the top of unit 1 (2 observed); lithofacies ICA.

1. Sand, silt and gravel: a poorly exposed deformed melange of medium to fine grained sand beds or lenses, medium to fine gravel lenses or beds, silt lenses or beds; greater than 2 m thick.

12. Island Bluff West DNP78 5

Location: Left bank of South Saskatchewan River at westernmost end of the slump scarp. NE14-5-14-5-W5

Elevation of the top of the section: 709 m (2325 ft)

Comments: Exposure is along west edge of slump block, some slumping may have occurred within it.

5. Diamicton: silty, sand; light yellowish brown (2.5Y 6 / 4 dry); oxidized; rare silt, sand and gravel lenses near top of exposure; large columnar structure (2 m x 1 m x thickness of unit); unlayered; contains a few large cobbles; forms steep cliff face in scarp; upper contact eroded by modern surface; lower contact sharp, wavy; unit is approximately 7 m thick; lithofacies DCL? / UD?

4. Gravel: sandy, poorly sorted; mainly pea gravel, some fine sand lenses; upper 10 cm is a sand bed; lower contact sharp unit is 1 m thick and extends laterally for about 20 m.

* moved along scarp to south west approximately 8 m and continued measurement.

3. Silt: laminated; poorly exposed; appears to underly unit 4 but may be lateral equivalent; unit thickness about 1 m.

2. Diamicton: clayey, silt; light grey (2.5Y 7 / 2 dry) to light brownish grey (2.5Y 6 / 2 dry);

oxidized; upper 2 m contains horizontal lenses or beds of very fine sand and silt; small blocky structure (1-2 cm^3) ; weak to moderate mottled yellowish red (5YR - 5/8 dry) joint face stain; lower contact sharp; unit is about 8 m thick; lithofacies undifferentiated.

1. Sand: fine to medium grained; oxidized; primarily cross-bedded, with mud and silt rip-up clasts in places; small worn shell fragments are common; fine to very fine sand and silt in the middle of the exposure; lowest part of unit appears to be cross-bedded; unit is greater than 5.5 m thick.

Evilsmelling Bluff

The upper part of the Quaternary sequence is exposed at this local(formation A, B, and C). It is of particular interest because of the very good exposure of formation B diamicton and the deformation within its lower and middle members.

13. Evilsmelling Bluff Centre DNP79 14

Location: On the right bank of the South Saskatchewan River
NW10-20-13-5-W4

Elevation of the top of the station: 711 m (2333 ft)

Comments: Measured from the top of a large slump block diagonally along the exposure westward to the top of the scree.

4. Diamicton: silty sand; dark grayish brown (2.5Y 4/2 dry); exhibits large columnar jointing (1 x 2 m x thickness of unit); unlayered; forms steep cliff face most of which is inaccessable here (upper 4m not examined); gradational basal contact; estimated thickness is 7 m; lithofacies UD?

3. Diamicton: clayey silt; light gray (2.5Y 7/2 dry) to light brownish gray (2.5Y 6/2 dry); large columnar jointed (1 x 2m x thickness of unit); contains numerous even, parallel undeformed, horizontal, very thin silt and sand laminae that are 2 to 10 cm apart; thinner (<1 mm) laminae have sharp contacts and winnow out to form horizontal joints, however throughout much of the diamicton there are silty, diamicton laminae, with gradational contacts that do not winnow out; basal contact not exposed here but approximately 30 cm away in cliff face it is sharp; unit is estimated to be 7 m thick; lithofacies SD.

2. Diamicton: clayey silt; light brownish gray (2.5Y 6/2 dry); layered; basal contact is sharp; unable to examine closely due to inaccessability of cliff; adjacent cliff face shows discontinuous horizontal sand and silt layers up to 10 cm thick, and isoclinal folds; estimated thickness 7.5 m; lithofacies LD.

1. Sand and silt: medium to fine sand grades upward to 1 to 2 m of weakly laminated silty sand at the top; most of the unit consists of finely laminated (1 mm thick) medium to fine sand with 10 - 20 cm thick massive silty sand beds in places; laminae are parallel with no cross lamination observed; laterally a pebbly gravel lens occurs near the top of this unit; highly oxidized organic detritus occurs at the base of the exposure; the entire unit is deformed with recumbent folds; 8 m of unit are exposed.

14. Evilsmelling Bluff Centre DNP79 11

Location: On right bank of the South Saskatchewan River in slump scarp starting at prairie level.
NE10-20-13-5-W4

Elevation of the top of the station: 716 m (2350 ft)

Comments: Measured from the top diagonally along the top of the scree slope from west to east over a lateral distance of approximately 20 m.

12. Silt and very fine sand: thickly bedded; good soil development on top; sharp lower contact; thickness estimated to be 2 m; not examined closely due to inaccessability.

11. Sand: medium to fine grained; cross-bedded; sharp lower contact; not examined closely due to inaccessability; thickness estimated to be 2 m, but highly variable.

10. Sand: fine to medium grained; plane and cross-bedded; commonly infills depressions in the top of unit 9; in places contains thin silt beds that exhibit penecontemporaneous deformation structures; eg. convolute bedding and slump structures; unit is discontinuous, and is recognized by its darker colour than unit 11; unit is up to 2 m thick.

9. Diamicton: silty, sand; olive (5Y 4 / 3 moist) to dark greyish brown (2.5Y 4 / 2 dry); exhibits large columnar jointing (1 x 2 m x thickness of unit); large, commonly deformed sand lenses occur within the top 1 to 5 m; these lenses typically exhibit vertical bedding, especially in larger lenses near the upper contact and may also exhibit normal faulting, with diamicton dikes along fault planes in places; lenses vary in size from 5 cm thick by 1 m long to 2 m by 3 m; lens boundaries follow bedding planes except where faulted; lower contact of unit is gradational; unit thickness varies from 5 to 7 m; lithofacies DCL.

8. Diamicton: silty, sand; olive brown (2.5Y 4 / 3 dry); unlayered; lower contact gradational; unit is approximately 3 m thick; lithofacies UD.

7. Diamicton: silty, sand; olive brown (2.5Y 4 / 3 dry); contains numerous undeformed, unfaulted, parallel, discontinuous very thin (0.1 to 5 mm, average less than 1 mm) beds of medium to coarse sand or laminated silt and very fine sand; sharp smooth lower contact; bedding is conformable with lower contact; unit thickness is 4 m; lithofacies SD.

6. Diamicton: clayey, silt; grey (5Y 5 / 1 dry) to greyish brown (2.5Y 5 / 2 dry); contains abundant deformed silt and sand layers 1 - 30 cm thick, average 3 cm; deformations include recumbent and isoclinal folds and reverse faulting; diamicton has a well developed blocky structure (2 - 3 cm^3); unit has a gradational lower contact and is 3.7 m thick; lithofacies LD.

5. Silty sand: upper 3 - 5 cm is weakly laminated medium to fine sand with small silt lenses in it; lower 5 cm is clayey silt; unit is horizontal and continuous across outcrop (> 20 m laterally), is undeformed and has a sharp lower contact; 10 cm thick.

4. Diamicton: clayey, silt; very dark grey (5Y 3 / 1 moist); to light brownish grey (2.5Y 6 / 2 dry); blocky structure (2-3 cm^3), contains abundant deformed silt and sand beds and lenses as in unit 6; joint faces are stained dark red (2.5Y 3 / 6 dry); lower 2 m is composed almost entirely of sand layers, commonly 10 to 50 cm long and 2 to 20 cm thick; many of the lenses are fault-bounded or boudin-shaped and commonly appear attenuated laterally along fracture planes that extend into the diamicton; there is gradation in some places from diamicton to sand and silt; lower contact is sharp, wavy; unit is 4 m thick; lithofacies LD.

3. Sand: medium to coarse grained; weakly laminated, fines upwards to silt in top 1 m; contains layers and lenses of carbonaceous material; upper 1 to 3 m is deformed with recumbent and isoclinal folds; horizontally bedded near base; lower contact is sharp and wavy, but poorly exposed; unit is 5.7 m thick.

2. Diamicton: silty, clay; very dark greyish brown (2.5Y 3 / 2 moist); to light olive grey (5Y 6 / 2 dry); irregular blocky structure (3 cm^3) with yellowish brown (10YR 5 / 6 dry) to

reddish yellow (7.5YR - 6/8 dry) stain in joints penetrating up to 5 mm into matrix; contains abundant irregular sand lenses with no visible primary structures; diamicton clast content 1 to 3%; basal contact is sharp, with horizontal platey structure near the contact in places; poorly exposed and may not be in place; unit is 0.9 to 1.0m thick; lithofacies undifferentiated.

1. Sand: fine to very fine grained; light yellow brown (2.5Y 6/4 dry); some cross-bedding and horizontal bedding; exposed only in a narrow trench; unit is at least 2.5 m thick, lower contact covered.

Golden Valley Bluff

This exposure is the most extensive in the area and has been used as a stratigraphic reference section. It also contains what is interpreted to be the most complete Pleistocene exposure in the area. All of the formations shown on Table 1.3 are present as well as good examples of most of the lithofacies. Several different types of deformation are also present. The best overview of the section is gained from the west side of the South Saskatchewan River.

15. Golden Valley North DNP81 10

Location: On the right bank of the South Saskatchewan River along the north side of gully number 2, approximately 50 m up the gulley from the river valley edge NE15-9-13-5-W4

Elevation of the top of the section: 709 m (2325 ft)

Comments: This section contains a large deformation structure.

2. Diamicton: silty, sand; light yellowish brown (2.5Y 6/4 dry); upper 2 m is horizontally layered, unable to examine closely; lower portion is unlayered, with a few vertical joints; no sand lenses; sharp lower contact; estimated thickness of 3.5 m.

1. Diamicton: clayey, silt; very dark grayish brown (2.5Y 3/2 dry); blocky structure (5 cm^3); prominent joint faces stained brownish yellow (10YR - 6/6 dry); contains numerous inclusions, some of which are unconsolidated, greyish in colour, elongate, lenticular and close to horizontal, less than 5 m long and 20 cm thick; there are also light brown sandstone blocks that are greater than 10 m long, up to 1.5 m thick and are heavily deformed; the base of the sansdtone block is marked by a thin rust coloured zone (< 20 cm thick) and is underlain by poorly exposed structureless diamicton closely resembling the rest of unit 2 diamicton; estimated thickness is 6 m; lithofacies UD?

16. Golden Valley North DNP79 17 and DNP80 52

Location: Right bank of South Saskatchewan River on the south side of gully number one NE15-9-13-5-W4

Elevation of the top of the section: 713 m (2339 ft)

Comments: Section was measured along the edge of the scree slope in a southward direction.

12. Diamicton: silty,sand; light yellowish brown to light brownish gray (2.5Y 6/3 dry); oxidized; about the upper 2 m is horizontally layered, unable to examine closely; lower portion is unlayered, with rare vertical joints; unit has a sharp lower contact, forms steep cliff and is about 8 m thick; lithofacies ?/UD?

11. Diamicton: clayey,silt; very dark greyish brown (2.5Y 3/2 dry); unlayered; blocky structure (5 cm^3); joint faces are stained brownish yellow (10YR 6/6 dry); contains a large deformed sand block and numerous deformed lenses and stringers; unit varies from 1 to 3 m in thickness; lithofacies UD?

10. Sand and Diamicton: lower 2 m is cross-bedded medium to fine sand that fines upwards into silt; above the silt, a one metre thick grayish brown (10YR 5/2 dry) diamicton with red (2.5YR 4/6 dry) joint staining occurs; this diamicton bed has deformed silt stringers and blebs near its base; overlying this diamicton is a sequence of thinly interbedded plane-bedded sand and structureless diamicton; the diamicton beds have sharp basal contacts, average 2 cm in thickness and occur about every 10 cm; the entire unit is wedge-shaped and discontinuous with a thickness of 1 to 2.5 m; basal contact of unit is sharp; lithofacies IDSS-T?

9. Diamicton: clayey,silt; light brownish grey (2.5Y 6/2 dry); blocky structure (3 cm^3); has heavy reddish brown (2.5YR 4/4 dry) joint stain; unlayered; lower contact is sharp and wavy; similar appearance to unit 7; varies from 2 to 6 m in thickness (6 m where measured). lithofacies UD?

8. Diamicton: clayey, silt; light brown grey (2.5Y 6/2 dry); blocky to platey structure; the bottom 6 m contains horizontally bedded, faulted and boudinaged fine sand and silt lenses up to 20 cm thick; with reddish brown (2.5YR 4/4 dry) joint stains; upper contact is marked by a 2 cm thick clay bed; lower contact is flat and sharp; unit is 11 m thick; lithofacies LD?

7. Silty sand: mainly unbedded, with some weak laminae; rare small gravelly lenses containing Canadian Shield rocks occur in places; unit fines upwards from medium sand to silt and is 6 m thick.

6. Sand: medium to fine grained; cross-bedded; poorly exposed; thickness varies from 3 to 6 m along about 50 m of outcrop.

5. Gravel: cobbly with abundant fines; poorly exposed; appears to be a lag remnant of unit 4; lower contact is sharp, uneven; unit is 20 cm thick.

4. Diamicton: silty, clay; olive gray to grayish brown (5Y 5.5/2 dry); heavily fractured with dark reddish brown (2.5YR 3/3 dry) stain on fracture faces; basal 10 cm contains abundant silt and clay smudges; lower contact is sharp and horizontal with scratches, and drag folds; clay along this lower contact is polished and waxy in appearance; unit is poorly exposed, is entirely eroded in places and reaches a maximum thickness of 1.5 m; lithofacies LD and UD (intermediate between the two?).

3. Silt and clay: weak horizontal and cross-laminae; several thin (less than 5 cm thick) cross-bedded sand beds occur towards the base of the unit; about 1 to 2 m from the top, the unit grades into rhythmically bedded clay and silt; the lower contact of the unit is gradational; unit is 6 m thick.

2. Sand: medium to fine grained; well sorted; largely tabular cross-bedded, with some subhorizontally laminated sand and rare silt lenses; coal fragment concentrations and clay rip-up clasts occur from place to place in trough cross-beds; intact wood/root segments are found in places, as detritus; gradational lower contact; unit is about 10 m thick.

1. Clayey silt and sandy silt: dark blue gray colour, unoxidized; even, parallel, bedded; interbedding of clayey silt and sandy silt beds; approximately 1 m exposed above late summer level of river.

17. Golden Valley North DNP81 8 (Lehr Gully area)

Location: On the right bank of the South Saskatchewan River approximately 50 m south of gully number 2.
SE15-9-13-5-W4

Elevation of the top of the section: 648 m (2125 ft)

Comments: Only the bottom of this section is accessible and therefore only it is described.

6. Diamicton: clayey, silt; grayish brown (2.5Y 5/2 dry); blocky structure (4 cm^3); with joint faces stained brownish yellow (10YR 6/6 dry); basal contact is sharp; bottom 2 m well exposed but overlying sediment is poorly exposed and inaccessible; thickness estimated to be 5m; lithofacies undifferentiated.

5. Silt: pale yellow (2.5Y 7/4 dry), fine horizontal laminated silt with minor thin (< 1 cm) interbeds of cross-laminated fine sand; gradational bottom contact; approximately 6 m thick.

4. Sand: medium to fine grained with trough cross-bedding and planar bedding; scours are up to 30 cm thick; small silt lenses interpreted as channel infill are common; clay rip-ups form bulk of cross-bedded units in places; white specks in the sand appear to be mainly shell fragments; lower contact is sharp; unit is 3 m thick.

3. Gravel: sandy, with clasts up to 30 cm in diameter, averaging 1 to 3 cm, contains Canadian Shield derived clasts; lower contact is sharp and erosional - probably a lag; thickness varies from 10 to 150 cm.

2. Diamicton: silty, clay; trace of stain in joints; diamicton is olive gray to grayish brown (5Y 5.5/2 dry) in colour; sharp , smooth, horizontal lower contact, with scratches on clay bedding planes along base; unit is discontinuous, occurs as small eroded lenses up to 50 cm thick and up to tens of m long; lithofacies UD?

1. Silt and clay: weak horizontal and cross-laminae; several thin (less than 5 cm) cross-laminated sand beds occur towards the base of the unit; load structures occur where fine sand and silt are interbedded; about 1 to 2 m from the top, the unit grades into rhythmically bedded clay and silt; the lower contact of the unit is not exposed; unit is > 6 m thick.

18. Golden Valley North DNP79 19

Location: On the right bank of the South Saskatchewan River just south of gully number 2
SE15-9-13-5-W4

Elevation of the top of the section: 697 m (2287 ft)

Comments: This is a very good exposure of most of the lower part of the sequence here.

9. Diamicton: clayey, silt; greyish brown (2.5Y 5/3 dry); unoxidized, blocky structure, (4

cm³) ; joint faces heavily stained brownish yellow (10YR -6/6 dry); clast content 1 - 3%, size range 1 - 4 cm; contains large lenses (5 to 25 cm long and 0.2 to 2 m thick) of fine sand and silt, especially in the lower 5 m; sand lenses contain very small shell fragments; some bedding and cross-laminae; and a few gravelly horizons; lower contact is subtle, wavy, defined on the basis of a change in structure, and a slight colour change; unit is approximately 12.5 m thick; lithofacies SD?

8. Diamicton: clayey, silt; very dark greyish brown (2.5Y 3/2 dry); platey structure; clast content 1 - 3%, ranging in size from 1 - 4 cm in diameter; small lenses of sand and stringers of silt and clayey sediment are common; lower contact is sharp and flat; 1.5 m thick; lithofacies SD?

7. Sand and Silt: fine to very fine grained; pale yellow (2.5Y 7/4 dry); horizontally laminated sand with rare cross-laminae and minor massive silt beds that are commonly less than 5 cm thick; sharp lower contact; unit is 7.6 m thick.

6. Sand: medium to fine grained; cross laminated; exhibits normal faulting with offsets of up to 10 - 15 cm; gradational basal contact; poorly exposed laterally; unit thickness varies from 0.5 to 1.3 m.

5. Gravel: sand to cobbles 4 cm in diameter; poorly sorted; fines upwards; predominantly Canadian Shield rocks with less than 10% quartzites; cross-bedding of sand and gravel beds is common; shows normal faulting that extends up through unit 6; sharp lower contact; occurs as small channel fill along base of unit 6 and cut into unit 4; appears to be lag remnant of unit 4; unit varies from 0.3 to 0.8 m thick.

4. Diamicton: silty, clay; dark olive grey (5Y 3/2 dry) to olive grey colour (5Y 4/2 dry); blocky structure (1 cm³); some reddish brown (2.5YR 3/3 dry) joint staining; clast content 1-3%; lower 30 to 50 cm grades upward to more clasts and possibly less silt and clay in the matrix; upper 20 cm is oxidized and contains a single sand dike approximately 20 cm by 4 cm and rectangular in cross section; lower contact zone is approximately 2 cm thick, consisting of closely spaced *en echelon* fractures that are confined to this basal zone, with sharp upper and lower contacts; unit where measured is 0.8 m thick but varies laterally from places where it has been eroded out, to about 1.5 m thick; lithofacies UD?

3. Silt and minor sand: weakly laminated with some cross-laminae; several thin (< 5 cm) cross-bedded sand beds occur towards the base of the unit; upper contact is sharp to gradational, with 20 to 30 cm of moderately deformed sediment, including small recumbent folds that gradually dissipate downwards; no faulting occurs in the clay at the top; load structures are common where sand overlies silt; lower contact gradational; unit is 6 m thick where measured but thins northward; excellent exposure.

2. Sand: medium to fine grained, well-sorted; largely tabular cross-bedded, with some subhorizontally bedded sand and rare silt beds; coal fragment concentrations and clay rip-up clasts occur from place to place in trough cross-beds that are up to 1 m deep; wood segments found intact, as buried detritus in sandy and silty clay beds; lower contact gradational; thickness is about 10 m.

1. Silt: dark blue grey colour; unoxidized; even, parallel bedded; poor exposure; only the upper 0.5 m is exposed.

19. Golden Valley North DNP79 16

Location: On the right bank of the South Saskatchewan River approximately 50 m south of gully number 3.
NE10-9-13-5-W4

Elevation of the top of the section: 641 m (2100 ft)

Comments: This portion of the section is largely inaccessible, but contains a very good exposure of the lowest diamicton and its lower contact.

4. Gravel: cobbly with abundant fines; poorly exposed; appears to be a lag remnant of unit 3; 0 to 1.5 m thick.

3. Diamicton: silty, clay: olive gray to gray brown (5Y 5.5/2 dry); trace of joint face stain; unlayered; the lower contact of the diamicton changes in character laterally from a sharp contact with a zone of disturbance in the underlying clay confined to less than 1 cm, to a zone of intensely fractured clay and diamicton up to 1 m thick. This zone is comprised of curved fractures that are closely spaced and delineate lenticular pieces of very compact, polished clayey sediment. The lower portion of this zone grades into underlying undisturbed rhythmically bedded silt and clay. In places drag folds? up to 3 cm in amplitude occur in the relatively undisturbed zones, where deformation is less then 5 cm thick; unit is 30 to 50 cm thick along 15 m of exposure.

2. Clay and silt: appears unbedded, but weak planar and cross-laminae occur; several thin (<5 cm) cross-bedded sand beds occur towards the base of the unit; fines upwards to upper 50 cm of rhythmically bedded clay and silt; lower contact gradational; excellent exposure; 6 m thick; lithofacies UD.

1. Sand: medium to fine grained; well-sorted; largely tabular cross-bedded, with some subhorizontally bedded sand and a few silt beds; loaded contacts where sand overlies silt are common; coal fragment concentrations and clay rip-up clasts occur from place to place in trough cross-beds; wood/root segments found intact, as buried detritus in sand and silty clay beds; lower contact is gradational; thickness is 10 m.

20. Golden Valley North DNP78 14

Location: On the right bank of the South Saskatchewan River along the north side of gully #4
NW9-9-13-5-W4

Elevation of the top of the section: 709 m (2325 ft)

Comments:
This is the best exposure of the bottom of formation A. Thickness of units not measured due to inaccessability of this section, but the base of formation A was examined closely.

4. Diamicton: silty, clay; greyish brown (2.5Y 5/2 dry); unlayered; weak blocky structure; forms steep cliff face in gully; attenuated fragments (less than 2 cm thick by 10 cm long) of silt and clay occur within the basal 10 cm ;contains a large deformed sandstone lense about 3 m thick by 8 m long that has been overfolded; basal contact of diamicton is sharp, horizontal; much of outcrop obscured by slump; estimated thickness is 8 m; lithofacies UD.

3. Clay: rhythmically bedded; locally deformed and is scratched on bedding plane surfaces; lower contact gradational; 80 cm thick.

2. Silt and fine sand: even, parallel laminated; rare gravel lenses and single pebbles; fines upwards from sand at base to silt with rare interbedding of sand and silt; lower contact gradational; about 6 m thick.

1. Sand: medium to fine grained; largely tabular cross-bedded, with some sub-horizontally laminated sand and rare silt lenses; coal fragment concentrations and clay rip-up clasts occur from place to place in trough cross-beds; about 10 m thick.

21. Golden Valley Bluff South DNP81 6

Location: On the right bank of the South Saskatchewan River, at the north end of the sewage lagoon terrace, in a gully that cuts into the cliff.
SW4-10-13-5-W4

Elevation of the top of the section: 743 m (2437 ft)

Comments: This is one of the deepest exposures at Golden Valley Bluff. Where a range of thickness is given for a unit, the variability was observed within approximately 10 m of the measurement site.

8. Silt and fine sand: light grey (10YR - 7 / 1 dry) to greyish brown (10YR 5 / 2 moist); thick-bedded (0.5 to 1 m); columnar jointed; no primary structures observed within beds; upper 1 to 1.5 m contains three or more poorly developed paleosols with subparallel jointing in lower 1.5 m that is likely along bedding planes; gradational lower contact; 3 m thick.

7. Diamicton: silty sand; light yellowish brown (2.5Y 6 / 4 dry); large columnar joints (1 m x 3 m x unit thickness); unlayered; top 0.5 m contains small horizontal lenses of silt and sand and discontinuous gravel lenses that in places exhibit collapse structures, including normal faulting; forms steep cliff; basal part of unit is unlayered; a few large boulders occur along lower contact; unit is 3.2 m thick; lithofacies DCL / UD.

6. Diamicton: clayey, silt; dark greyish brown (2.5Y 4 / 2 moist); strong blocky structure (1 to 4 cm^3 blocks); joint faces stained dark red (2.5YR - 3 / 6 dry);more recessive than overlying diamicton; forms vertical cliff; upper 0.5 - 1 m contains a few small sand stringers; basal 2 m contains laminated silty sand lenses that are commonly deformed, and / or microfaulted; some laminae are nearly vertical, light grey to pale yellow (2.5Y 7 / 2 dry); lenses appear to be fragments - incorporated and deformed by overriding ice or primary soft sediment deformation; lower contact gradational; unit is 6.0 m thick; lithofacies SD / LD?

5. Diamicton and sand: silty clay diamicton 0.5 to 20 cm thick, interbedded with horizontal discontinuous silty sand and sand lenses (0.5 to 3 cm thick); greyish brown to light greyish brown colour (2.5Y 4.2 dry); diamicton has moderate blocky structure; weak horizontal laminae in silt and sand lenses; lower contact gradational; no deformation; unit is 1.7 m thick; lithofacies SD?

4. Sand: fine grained; horizontal, undeformed laminae; sharp, horizontal basal contact; unit

is 0.5 to 1.5 m thick.

3. Sand: light olive brown (2.5Y 5 / 4 dry); fines upwards from cross-bedded medium to coarse sand at base with rare pebbles up to 2 cm in diameter; laterally along outcrop locally deformed, cross-bedding shows collapse structures (synclinal forms); sharp lower contact; unit is 1 to 2 m thick.

2. Diamicton: silty clay; greyish brown (2.5Y 5 / 2 dry); contains abundant beds, small lenses, and discontinuous stringers of sand, silty sand and poorly sorted fine gravel; lenses are commonly laminated or cross-laminated, with little deformation and are generally 5 - 10 cm thick; unit is 2 m thick (varies from 1-3 m along outcrop); lithofacies LD?

1. Diamicton: silty clay; greyish brown (2.5Y 5 / 2 dry); weak blocky structure, prominent vertical joints with staining and gypsum; stain penetrates approx 1 cm from joint faces; contains abundant large irregular highly deformed sandy silt lenses (collapse and injection structures); about the upper 2 m has conspicuous horizontal subparallel joints (partings) that contain no fines; from about 8 to 15 m below the top of the unit there are horizontal beds of silt and silty clay, some of which are composed of massive, very fine sand; 17.9 m thick; lithofacies IDSS-T / DSD.

22. Golden Valley Bluff Centre DNP78 13

Location: On right bank of South Saskatchewan River, at the north end of the sewage lagoon terrace, in a gully that cuts into the cliff.
SW4-10-13-5-W4

Elevation of the top of the section: 747 m (2450 ft)

Comments:

8. Sandy Silt: grayish brown (10YR 5 / 2dry); (3 x 3 x 10cm);columnar structure; thick-bedded; unit is 3.2 m thick

7. Diamicton: silty sand; light yellowish brown (2.5Y 6 / 4 dry); weak columnar joints; upper 1.5 m is very recessive; containing small horizontal lenses of sand, silt and gravel, some lenses are normally faulted; diamicton has a clast content of approximately 3 % by volume; basal 3.7 m forms 70-80^{0} cliff face and has a unlayered structure; basal contact is sharp and planar; unit is 5.2 m thick; lithofacies DCL / UD.

6. Diamicton: clayey silt; dark greyish brown (2.5Y 4 / 2 moist); strong blocky structure; more recessive than unit 7; but forms a near vertical cliff face; dark red (2.5YR -3 / 6 dry) joint face stain; laminated sand and silt lenses occur throughout the unit; in some places where diamicton appears unlayered, close examination shows horizontal partings like fractures. In these places, the diamicton exhibits some flow structures and contains rounded, unconsolidated clay and silt clasts; contacts between silt or sand lenses and diamicton are sharp and no gradation was observed in the diamicton that exhibits partings; the diamicton in this unit is approximately 3 to 5% clasts by volume, with average clast size less than 1 cm; basal contact of unit is sharp, unit is 6 m thick; lithofacies SD and DSD..

5. Diamicton and sand: silty clay diamicton interlayered with deformed discontinuous

irregular silty sand layers; diamicton is olive brown (2.5Y 4/4 moist) with a moderate blocky structure (4 x 2 x 2 cm^3); diamicton has more clasts than overlying unit; basal contact is sharp; unit is 3.6 m thick; lithofacies LD.

4. Silty sand: fine grained; olive yellow (2.5Y 6/6 dry) to light yellowish brown (2.5Y 6/3 dry); predominantly massive, with some weak lamination; undeformed; lower contact is gradational; unit is 70 cm thick.

3. Sand: fine to medium grained; light brownish gray to light yellowish brown (2.5Y 6/3 dry); cross bedded; exhibits synformal collapse type deformation; gradational basal contact; 1 m thick.

2. Sand and diamicton: light brownish gray (2.5Y 6/2 dry); oxidized; each interbed consists of 1-3 cm of silty clay diamicton at the base, overlain by a 1-3 cm of sand; the diamicton contains rounded unconsolidated diamicton clasts; contacts between these lithologies is sharp; synformal collapse type deformation is common; soft, white carbonate deposits (nodules?) averaging 2 cm^3 in vertical thickness but up to 6 cm horizontally, occur in zones within sand beds; elsewhere, sand beds contain white carbonate flecks that may be shell fragments but are too weathered to determine; sharp basal contact; unit is 1 m thick; lithofacies IDSS-T.

1. Diamicton: silty clay; dark grayish brown (2.5Y 4/2 dry) to very dark grayish brown (2.5Y 3/2 moist); the basal 24 m of the unit that are exposed here (basal contact not exposed) have a weak blocky structure and prominent vertical joints that are stained rust brown and contain gypsum; the stain penetrates up to 1 cm from joint faces; diamicton is unlayered, with abundant sandstone blocks and large irregular highly deformed sandy silt lenses; when the outcrop is wet and is viewed from a distance, some sand lenses were observed to be deformed with vertical stringers extending upwards from upturned ends; close examination revealed parallel bands of silt, silty clay and very fine sand; no primary structures observed within them; unit forms steep 70-90° cliff face; upper 1-3 m contains abundant small lenses and discontinuous beds of sand; silty sand and in a few places fine gravel; lenses are commonly 5-10 cm thick and laminated or cross laminated with only minor deformation; 27 m of unit are exposed; lithofacies IDSS-T/DSD.

23. Golden Valley Bluff South DNP82 8A

Location: On the north side of the Medicine Hat Dump, at prairie level, at the east end of an east-west trending exposure.
SW12-10-13-5-W4

Elevation of the top of the section: 747 m (2450 ft)

Comment;

3. Diamicton: clayey silt; dark grayish brown (2.5Y 4/2 dry); can be traced along outcrop to unit 3 at DNP82-8b; contains a large deformed block of sand ; unit is > 5 m thick; poorly exposed; lithofacies UD?

2. Diamicton, silt and sand: approximately the basal 1 m is weakly laminated silt and very fine sand with no stones or debris bands; grades upwards into an interbedded sequence of silt beds (up to 50 cm thick), massive sand beds 20 - 50 cm thick and diamicton beds 2 - 10 cm thick that contain clasts up to small cobbles in size. Entire unit is moderately

deformed; unit is 5 m thick; lithofacies IDSS-T.

1. Diamicton: silty, clay; greyish brown (2.5Y 5 / 2 dry) small blocky structure (1 cm^3); contains deformed sand lenses that are generally small, lenticular and appear to be intact and close to their depositional orientation; about 2 m of this unit is exposed; lithofacies undifferentiated.

24. Golden Valley Bluff South DNP82 8B

Location: On the north side of the Medicine Hat Dump, at prairie level, in the middle of an east-west trending exposure. Approximately 20 m east of DNP82-8A.
SW12-10-13-5-W4

Elevation of the top of the section: 747 m (2450 ft)

Comments:

3. Diamicton: silty, sand; light yellowish brown (2.5Y 6 / 4); large columnar joints (1 x 2 m x thickness of unit) unlayered; poorly exposed; forms steep cliff in lower part of unit, but upper part is recessive; unit is 2 m thick; lithofacies undifferentiated.

2. Diamicton: clayey, silt; dark greyish brown (2.5Y 4 / 2); blocky structure (1-4 cm^3); unlayered; dark red joint stain (2.5YR -3 / 6 dry); recessive; thickness 0.2 to 2 m within 10 m of station; lithofacies undifferentiated.

1. Fine sand, silt and diamicton interbedded: thick bedded massive silt (10 -20 cm), interbedded with thin (2 - 5 cm) diamicton beds that are dark grayish brown (2.5Y 4 / 2 dry); diamicton beds are commonly overlain by thin medium to fine grained sand beds that are cross-bedded and pale yellow (5Y 6 / 4 dry); silt beds are brown to grey in colour, contain coal fragments and clay balls; silty sand beds are reddish yellow (5YR - 6 / 6 dry); unit is 1.5 m thick; entire unit is deformed in an anticlinal structure where exposed; lithofacies IDSS-T.

25. Golden Valley Bluff South DNP82 8C

Location On the north side of the medicine Hat Dump, at prairie level, at the east end of an east-west trending exposure. Approximately 35 m east of DNP82-8C.
SW12-10-13-5-W4

Elevation of the top of the section: 747 m (2450 ft)

Comments:

4. Diamicton: sandy, silt; large columnar joints; unlayered; forms steep cliff (70 - 80^0); upper part is recessive; unit is 2 m thick; small flutes on base at 110 - 290^0; lithofacies UD?

3. Sand: medium to fine grained, pale yellow (2.5Y 7 / 4 dry); plane-bedded; fines upwards

to sandy silt at the top that has concentrations of coal fragments at its base and contains thin (0.5 cm) laminae of silty clay; no pebbles; minor gravel lens at the base of the unit; unit is 1.5 m thick.

2. Diamicton: silty, clay; dark grayish brown (2.5Y 4 / 2 dry); strong blocky structure (1 - 4 cm^3); unlayered; recessive; stained joint faces, dark red (2.5YR - 3 / 6 dry); forms vertical cliff; unit is 2 m thick; lithofacies UD?

1. Sand and silt: medium to fine grained; plane-bedded. This unit is not well enough exposed to determine if it is within the diamicton (unit 2) or underlies it; > 1.5 m thick.

27. Golden Valley Bluff South DNP82 100

Location: On the right bank of the South Saskatchewan River at the south end of the sewage lagoon terrace in a gully that cuts into the cliff.
NE11-33-12-5-W4

Elevation of the top of the section: 747 m (2450 ft)

Comments: This is one of the few accessible places along this section where formation B is undeformed.

9. Diamicton: sandy, silt; light yellowish brown (2.5Y 6 / 4 dry); large columnar joints; unlayered; forms steep cliff; 1.5 m thick; lithofacies UD?

8. Diamicton: silty, clayey; dark greyish brown (2.5Y 4 / 2 dry); moderate blocky structure; more recessive than overlying diamicton; has secondary cross cutting fractures; 1.5 m thick; part of lithofacies IDSS-T.

7. Diamicton, Silt and Sand: even parallel interbedded silty sand and diamicton; diamicton is dark greyish brown (2.5Y 4 / 2 dry); each diamicton bed, ranges from 0.5 to 20 cm thick, is predominantly composed of agglomerated diamicton balls and is overlain by plane-bedded to cross-laminated sand or silty sand beds, 1 to 20 cm thick; sand beds contain a few very thin silty sand laminae; no rip-up clasts observed in sand; lower diamicton contacts are sharp, upper contacts are sharp; unit is 1.5 m thick; lithofacies IDSS-T.

6. Silty Clay: no bedding observed; poorly exposed; upper and lower contacts gradational; 0.4 m thick.

5. Sand: fine to very fine grained, unbedded; sharp basal contact; 1.4m thick.

4. Gravel: fine to coarse; sand in the interstices; lower contact is sharp, erosional; 0.2 m thick.

3. Sand and Silt: weakly bedded to unbedded; gradational lower contact; 1 m thick.

2. Diamicton: silty, clay; greyish brown (2.5Y 5 / 2 dry); abundant small lenses and

discontinuous stringers of sand and silty sand and clay; estimated thickness is 1 to 2 m. Inaccessible - not examined closely, but easily correlated visually with DNP78-13.

1. Diamicton: greyish brown (2.5Y 5 / 2 dry); > 15 m thick. Inaccessible, but easily correlated visually with DNP78-13.

28. Golden Valley South DNP81 7

Location: On the right bank of the South Saskatchewan River at the north end of the cliff that is just east of the IXL Brickyard.
SW11-33-12-5-W4

Elevation of the top of the section:

Comments: Only the lowermost units of the sequence are well enough exposed to measure. Description goes down to within 1 m of river level.

3. Diamicton: silty, clay; dark olive gray (5Y -3 / 2 dry); unlayered? blocky structure (3 cm^3); reddish brown (2.5YR -3 / 3 dry); joint staining; sharp basal contact; poorly exposed; unit is >3 m thick; lithofacies undifferentiated.

2. Sandy silt to fine sand: weakly laminated, thickly bedded silt with sand beds up to 10 cm thick; grades upward to rhythmically silt and clay that is about 30 cm thick; basal contact is gradational; unit is 6 m thick.

1. Sand: medium to fine sand; well sorted; predominately trough and tabular cross-bedded; clay rip-up clasts occur in some trough cross-beds; wood - twig segments found in some thin silt beds (<3 cm thick); basal contact buried; unit >5 m thick.

APPENDIX B: COARSE SAND LITHOLOGY DATA

Data are for the 1-to-2-mm size fraction of diamicton samples.

Terminology used in Appendix B

FM.K - formation key used by computer program to identify formation and members

FACIES - lithofacies
- UD - unlayered diamicton
- LD - layered diamicton
- SD - stratified diamicton
- IDSS - interbedded diamicton, sand, and silt
- U - lithofacies undifferentiated
- ? - lithofacies classification uncertain

PLOC - percentage of local rocks (sandstone+siltstone+shale)

PCS - percentage of Canadian Shield material (granites+mafics)

PCARB - percentage of carbonates (limestone+dolostone+dolomitic siltstone)

PGR - percentage of granite fragments

PMAF - percentage of mafics

PLST - percentage of limestone

PDOL - percentage of dolostone

LS/D - limestone/dolostone ratio

ID - sample identification number, refer to Appendix C (YR.S, SNUM, DEPTH) for site identification shown in figure 2.2

99.9 - analysis value of 99.9 indicates missing data

FM.K	FACIES	PLOC	PCS	PCARB	PGR	PMAF	PLST	PDOL	LS/D	ID
1	LD?	.139	.523	.337	.170	.044	.104	.005	20.800	114
1	LD?	.144	.541	.314	.179	.038	.116	.010	11.600	115
1	UD	.188	.547	.263	.175	.031	.099	.000	21.500	92
1	UD	.275	.375	.348	.070	.054	.112	.003	37.333	402
1	UD	.347	.286	.366	.118	.032	.139	.053	2.622	26
1	UD	.102	.403	.494	.151	.022	.179	.033	5.424	328
1	UD	.340	.255	.403	.078	.057	.156	.000	1.446	23
1	UD	.176	.353	.470	.142	.000	.166	.023	7.217	572
1	UD	.318	.296	.384	.127	.022	.127	.066	1.924	28
1	UD	.225	.368	.406	.107	.060	.133	.030	4.433	327
1	UD	.368	.199	.431	.069	.030	.153	.061	2.508	24
1	UD	.139	.332	.527	.102	.036	.176	.007	25.142	403
1	UD	.190	.333	.476	.113	.013	.140	.000	2.622	27
1	UD	.381	.166	.451	.052	.035	.188	.047	4.000	334
1	UD	.315	.302	.382	.121	.018	.134	.036	3.722	29
1	UD	.162	.469	.368	.129	.076	.114	.038	3.000	329
1	UD	.324	.260	.415	.084	.037	.143	.050	2.860	335
1	UD?	.504	.397	.097	.310	.031	.069	.015	4.600	555
1	DSD	.277	.486	.235	.195	.047	.100	.017	5.882	120
1	DSD	.210	.469	.319	.139	.046	.120	.003	40.000	121
1	DSD	.243	.473	.283	.137	.040	.086	.015	5.733	122
1	U	.316	.454	.229	.164	.014	.086	.004	21.500	88
1	U	.095	.599	.305	.220	.031	.085	.012	7.083	337
1	U	.152	.487	.359	.154	.044	.110	.022	5.000	117
1	U	.018	.538	.443	.144	.032	.081	.032	2.531	341
1	U	.092	.587	.319	.199	.049	.084	.049	1.714	339
3	LD	.116	.377	.506	.186	.057	.117	.209	.559	66
3	LD	.130	.266	.602	.089	.023	.103	.132	.780	356
3	LD	.600	.249	.150	.090	.033	.066	.008	8.250	106
3	LD	.137	.386	.475	.151	.049	.090	.030	3.000	110
3	LD	.184	.286	.528	.119	.061	.082	.250	.328	67
3	LD	.283	.333	.383	.112	.048	.104	.032	3.250	400
3	LD	.306	.278	.415	.074	.028	.133	.011	12.090	108
3	LD	.263	.373	.363	.161	.052	.067	.130	.515	111
3	LD	.609	.203	.187	.072	.032	.072	.016	4.500	107
3	LD	.171	.501	.326	.330	.012	.122	.085	1.435	370
3	LD	.145	.321	.532	.130	.042	.122	.141	.865	109
3	LD	.443	.142	.414	.066	.007	.154	.022	7.000	358
3	LD	.213	.480	.306	.337	.025	.175	.056	3.125	371
3	LD	.331	.235	.432	.075	.025	.134	.050	2.680	359
3	LD	.203	.592	.203	.318	.057	.101	.028	3.607	372
3	LD?	.376	.489	.134	.221	.026	.062	.006	10.333	84
3	LD?	.109	.709	.180	.563	.025	.033	.117	.282	567
3	LD?	.220	.483	.295	.236	.009	.150	.000	1.898	86
3	LD?	.269	.342	.388	.098	.046	.108	.023	4.695	391
3	LD?	.288	.365	.345	.167	.014	.112	.059	1 898	85
3	LD?	.174	.406	.419	.130	.026	.115	.020	5.750	395
3	LD?	.350	.377	.272	.123	.032	.096	.016	.6.000	87
3	LD?	.280	.212	.507	.080	.023	.187	.043	4.348	393
3	LD?	.657	.228	.114	.210	.000	.105	.000	1.255	565
3	LD?	.105	.291	.603	.076	.048	.184	.065	2.830	392
3	LD?	.154	.343	.501	.103	.048	.166	.051	3.254	394
3	IDSS	.161	.359	.479	.117	.050	.106	.026	4.076	46
3	IDSS	.068	.360	.570	.198	.038	.160	.213	.751	48

FM.K	FACIES	PLOC	PCS	PCARB	PGR	PMAF	PLST	PDOL	LS/D	ID
3	IDSS	.056	.433	.509	.200	.030	.140	.130	1.076	47
3	IDSS	.517	.183	.299	.016	.075	.116	.033	3.515	49
3	IDSS	.559	.201	.239	.092	.028	.121	.022	5.500	330
3	IDSS	.136	.327	.535	.158	.029	.128	.089	1.438	12
3	IDSS	.309	.202	.487	.084	.038	.130	.095	1.368	331
3	IDSS	.192	.400	.406	.203	.040	.108	.022	4.909	16
3	IDSS	.136	.327	.535	.158	.029	.128	.089	1.438	13
3	IDSS	.122	.416	.461	.198	.027	.102	.069	1.478	20
3	IDSS	.308	.375	.316	.122	.031	.098	.031	3.161	15
3	IDSS	.091	.371	.536	.079	.027	.123	.030	4.100	18
3	IDSS	.424	.196	.378	.088	.014	.094	.065	1.446	21
3	IDSS	.177	.576	.246	.290	.026	.035	.077	.454	17
3	IDSS	.071	.482	.446	.160	.028	.108	.028	3.857	19
3	UD?	.359	.226	.414	.051	.036	.134	.025	5.360	50
3	UD?	.195	.353	.451	.082	.103	.226	.010	22.600	52
3	SD	.069	.590	.340	.376	.077	.065	.195	.333	368
3	SD	.096	.465	.437	.169	.077	.073	.158	.462	64
3	SD	.157	.452	.389	.184	.052	.102	.078	1.307	320
3	SD	.183	.312	.503	.120	.078	.114	.205	.556	65
3	SD	.094	.584	.321	.373	.073	.089	.155	.574	369
3	SD	.184	.373	.442	.137	.021	.101	.086	1.174	324
3	SD	.052	.435	.512	.182	.044	.085	.117	.726	322
3	SD	.051	.421	.526	.176	.019	.171	.073	2.342	326
3	SD	.096	.377	.525	.143	.013	.136	.061	2.229	321
3	SD	.000	.600	.400	.148	.074	.037	.111	.333	325
3	SD	.250	.260	.489	.102	.019	.177	.047	3.765	323
3	SD ?	.202	.283	.513	.126	.053	.142	.182	.780	70
3	SD ?	.187	.292	.520	.153	.056	.139	.190	.731	68
3	SD ?	.057	.404	.538	.228	.052	.122	.251	.486	74
3	SD ?	.257	.270	.472	.146	.033	.074	.238	.310	69
3	SD ?	.105	.353	.541	.169	.056	.116	.229	.506	72
3	SD-L	.146	.342	.511	.118	.051	.112	.105	1.066	364
3	SD-L	.244	.471	.283	.182	.026	.074	.051	1.450	59
3	SD-L	.309	.257	.432	.079	.026	.109	.018	6.055	352
3	SD-L	.094	.304	.600	.127	.050	.145	.169	.857	332
3	SD-L	.201	.262	.536	.088	.036	.095	.118	.805	353
3	SD-L	.126	.399	.474	.156	.053	.129	.119	1.084	333
3	U	.500	.375	.124	.105	.052	.000	.052	.000	34
3	U	.138	.500	.361	.157	.031	.094	.042	2.238	399
3	U	.107	.609	.283	.436	.036	.089	.131	.679	35
3	U	.150	.354	.495	.153	.035	.117	.089	1.314	354
3	U	.302	.321	.376	.083	.074	.162	.013	12.461	397
3	U	.138	.325	.536	.120	.037	.105	.154	.681	361
3	U	.136	.320	.542	.123	.041	.108	.097	1.113	398
3	U	.068	.116	.814	.048	.017	.414	.039	10.615	363
4	LD?	.189	.644	.165	.357	.024	.024	.074	.324	81
4	LD?	.303	.601	.095	.317	.018	.051	.002	25.500	80
4	LD?	.324	.554	.121	.217	.012	.048	.002	24.000	82
4	UD	.103	.583	.312	.207	.041	.069	.041	1.682	350
4	UD	.137	.417	.444	.163	.037	.105	.023	4.565	9
4	UD	.106	.640	.252	.380	.052	.067	.089	.752	571
4	UD	.138	.582	.278	.215	.038	.080	.034	2.352	53
4	UD	.163	.432	.404	.183	.047	.102	.061	1.672	351
4	UD	.170	.657	.171	.543	.036	.065	.086	.755	32

FM.K	FACIES	PLOC	PCS	PCARB	PGR	PMAF	PLST	PDOL	LS/D	ID
4	UD	.189	.473	.336	.201	.017	.090	.035	2.571	396
4	UD	.394	.469	.136	.189	.017	.058	.002	29.000	101
4	UD	.123	.417	.459	.217	.043	.113	.173	.653	568
4	UD	.113	.471	.415	.188	.024	.066	.049	1.346	11
4	UD	.176	.538	.285	.246	.029	.062	.075	.826	57
4	UD	.147	.372	.479	.144	.048	.103	.133	.774	33
4	UD	.199	.530	.269	.210	.016	.046	.004	11.500	104
4	UD	.223	.469	.306	.111	.042	.076	.024	3.166	10
4	UD	.170	.561	.268	.206	.035	.054	.059	.915	55
4	UD	.207	.492	.300	.161	.024	.107	.006	17.833	103
4	UD	.279	.504	.216	.231	.058	.066	.011	6.000	105
4	UD?	.190	.562	.246	.233	.041	.055	.065	.846	38
4	UD?	.075	.606	.317	.228	.020	.046	.084	.547	61
4	UD?	.147	.472	.380	.146	.040	.059	.036	1.638	43
4	UD?	.052	.689	.258	.237	.038	.015	.088	.170	63
4	U	.110	.444	.444	.095	.095	.095	.095	1.000	349

APPENDIX C: GRANULOMETRIC AND CLAY MINERALOGY DATA

The sample analyses listed below are for diamicton samples.

Terminology used in Appendix C

FM.K - formation key (used computer program to identify formation and member

FACIES - lithofacies name (same as for Appendix B)
? - lithofacies classification uncertain
U - lithofacies undifferentiated

SAND - percent sand

SILT - percent silt

CLAY - percent clay

K - kaolinite

ILL - Illite

MONT - montmorillonite

CHL - chlorite

ID - sample identification number (same as in Appendix B)

YR.S - year sampled (all sample sites shown on map, Figure 2.2, followed by SNUM are prefixed by DNP)

SNUM - sample number

DEPTH - sample depth (a depth of 0 indicates that sample was located using a reference plane, eg. a member contact)

FORMATION - formation and member
C - formation C
B - formation B
MB - middle member of formation B
UB - upper member of formation B
A - formation A

99.9 - a value of 99.9 indicates missing data

FM.K	FACIES	SAND	SILT	CLAY	K	ILL	MONT	CHL	ID	YR.S	SNUM	DEPTH	DMOD	FORMATION
1	LD?	39.0	29.0	32.0	14.0	33.0	47.0	6.0	114	78	13	18.0		A
1	LD?	40.0	28.0	32.0	20.0	37.0	38.0	6.0	115	78	13	18.6		A
1	UD	12.0	48.0	40.0	13.0	37.0	47.0	3.0	23	78	4	21.0		A
1	UD	9.0	53.0	38.0	12.0	29.0	54.0	4.0	24	78	4	23.0		A
1	UD	16.0	45.0	39.0	11.0	40.0	46.0	3.0	25	78	4	24.0		A
1	UD	11.0	50.0	39.0	14.0	36.0	45.0	6.0	26	78	4	27.0		A
1	UD	12.0	52.0	36.0	10.0	39.0	41.0	10.0	27	78	4	29.0		A
1	UD	14.0	46.0	40.0	7.0	33.0	54.0	6.0	28	78	4	30.0		A
1	UD	11.0	49.0	40.0	12.0	37.0	48.0	3.0	29	78	4	31.0		A
1	UD	1.0	62.0	37.0	11.0	41.0	45.0	3.0	30	78	4	33.0		A
1	UD	25.0	30.0	45.0	11.0	28.0	56.0	5.0	89	78	12	16.0		A
1	UD	27.0	36.0	37.0	21.0	37.0	42.0	.0	90	78	12	17.0		A
1	UD	11.0	37.0	53.0	15.0	43.0	37.0	5.0	91	78	12	18.0		A
1	UD	15.0	37.0	48.0	12.0	30.0	52.0	6.0	92	78	12	19.0		A
1	UD	17.0	44.0	40.0	99.9	99.9	99.9	99.9	93	78	12	20.0		A
1	UD	24.0	40.0	36.0	11.0	29.0	60.0	.0	94	78	12	21.1		A
1	UD	99.9	99.9	99.9	10.0	32.0	54.0	4.0	95	78	12	22.0		A
1	UD	20.0	42.0	38.0	99.9	99.9	99.9	99.9	96	78	12	23.0		A
1	UD	25.0	40.0	35.0	14.0	31.0	55.0	.0	97	78	12	24.0		A
1	UD	15.0	42.0	44.0	99.9	99.9	99.9	99.9	98	78	12	25.0		A
1	UD	17.0	43.0	40.0	99.9	99.9	99.9	99.9	99	78	12	26.0		A
1	UD	16.0	42.0	42.0	10.0	26.0	64.0	.0	100	78	12	27.0		A
1	UD	37.0	29.0	34.0	9.0	40.0	44.0	6.0	128	78	15	34.0		A
1	UD	37.0	29.0	34.0	18.0	46.0	29.0	7.0	129	78	15	34.0		A
1	UD	10.0	50.0	40.0	99.9	99.9	99.9	99.9	327	79	6	1.0		A
1	UD	15.0	47.0	39.0	99.9	99.9	99.9	99.9	328	79	6	2.0		A
1	UD	10.0	49.0	40.0	99.9	99.9	99.9	99.9	329	79	6	3.0		A
1	UD	10.0	50.0	41.0	99.9	99.9	99.9	99.9	334	79	7	12.0	A	A
1	UD	10.0	49.0	42.0	99.9	99.9	99.9	99.9	335	79	7	12.0	B	A
1	UD	11.0	32.0	57.0	13.0	48.0	30.0	9.0	402	79	19	27.3	A	A
1	UD	13.0	41.0	46.0	12.0	43.0	35.0	10.0	403	79	19	27.3	B	A
1	UD	4.0	37.0	59.0	13.0	46.0	31.0	11.0	404	79	19	27.3	C	A
1	UD	12.4	48.2	39.4	99.9	99.9	99.9	99.9	572	81	13	17.3		A
1	UD?	16.0	46.0	38.0	14.0	36.0	42.0	8.0	126	78	14	.0	A	A
1	UD?	21.0	45.0	34.0	14.0	42.0	36.0	8.0	127	78	14	.0	B	A
1	UD?	13.6	48.9	37.6	11.0	42.0	34.0	13.0	555	80	50	.0		A
1	IDSS-T	27.0	40.0	33.0	14.0	42.0	38.0	7.0	119	78	13	22.3		A
1	IDSS-T	12.0	38.0	50.0	11.0	34.0	50.0	4.0	120	78	13	23.0		A
1	IDSS-T	12.0	40.0	48.0	99.9	99.9	99.9	99.9	121	78	13	25.0		A
1	IDSS-T	11.0	40.0	49.0	14.0	35.0	51.0	.0	122	78	13	27.0		A
1	IDSS-T	13.0	41.0	46.0	13.0	31.0	56.0	.0	123	78	13	29.0		A
1	IDSS-T	27.0	39.0	34.0	12.0	30.0	58.0	.0	124	78	13	46.0		A
1	U	18.0	37.0	45.0	9.0	27.0	59.0	5.0	88	78	12	13.0		A
1	U	12.0	47.0	41.0	9.0	27.0	64.0	.0	116	78	13	19.5		A
1	U	13.0	36.0	51.0	15.0	30.0	56.0	.0	117	78	13	20.0		A
1	U	16.0	41.0	43.0	11.0	35.0	49.0	4.0	118	78	13	21.0		A
1	U	9.0	43.0	48.0	17.0	35.0	48.0	.0	336	79	8	28.0		A
1	U	21.0	42.0	37.0	8.0	38.0	46.0	8.0	337	79	8	32.0		A
1	U	12.0	43.0	45.0	17.0	37.0	46.0	.0	338	79	8	34.0		A
1	U	16.0	41.0	43.0	99.9	99.9	99.9	99.9	339	79	8	36.0		A
1	U	17.0	44.0	39.0	99.9	99.9	99.9	99.9	340	79	8	41.0		A
1	U	15.0	45.0	40.0	17.0	39.0	44.0	.0	341	79	8	43.0		A
2	LD?	37.1	34.8	28.2	17.0	47.0	29.0	7.0	567	80	53	.0	U1	LB

FM.K	FACIES	SAND	SILT	CLAY	K	ILL	MONT	CHL	ID	YR.S	SNUM	DEPTH	DMOD	FORMATION
2	IDSS	25.0	44.0	31.0	99.9	99.9	99.9	99.9	45	78	8	14.5		LB
2	IDSS	25.0	46.0	29.0	8.0	37.0	49.0	5.0	46	78	8	15.5		LB
2	IDSS	99.9	99.9	99.9	7.0	46.0	31.0	16.0	47	78	8	16.0		LB
2	IDSS	99.9	99.9	99.9	12.0	46.0	27.0	15.0	48	78	8	17.0		LB
2	IDSS	10.0	52.0	38.0	8.0	25.0	62.0	5.0	49	78	8	18.0		LB
2	UD?	31.0	37.0	32.0	12.0	32.0	54.0	2.0	39	78	7	6.0		LB
2	UD?	12.0	48.0	40.0	5.0	27.0	64.0	4.0	50	78	8	20.5		LB
2	UD?	9.0	55.0	37.0	99.9	99.9	99.9	99.9	51	78	8	21.0		LB
2	UD?	8.0	53.0	39.0	7.0	39.0	46.0	8.0	52	78	8	21.5		LB
2	U	20.0	40.0	40.0	9.0	33.0	54.0	4.0	41	78	7	11.0		LB
2	U	20.0	43.0	37.0	99.9	99.9	99.9	99.9	42	78	7	12.0		LB
3	LD	29.0	37.0	34.0	19.0	51.0	25.0	5.0	66	78	10	8.0		MB
3	LD	31.0	35.0	34.0	24.0	42.0	31.0	4.0	67	78	10	9.0		MB
3	LD	14.0	50.0	36.0	8.0	26.0	65.0	.0	106	78	13	5.5		MB
3	LD	12.0	47.0	41.0	99.9	99.9	99.9	99.9	107	78	13	7.5		MB
3	LD	18.0	37.0	45.0	9.0	28.0	61.0	2.0	108	78	13	10.5		MB
3	LD	21.0	38.0	41.0	8.0	30.0	57.0	5.0	109	78	13	11.5		MB
3	LD	15.0	40.0	45.0	7.0	32.0	54.0	7.0	110	78	13	12.5		MB
3	LD	13.0	43.0	44.0	6.0	33.0	57.0	4.0	111	78	13	13.5		MB
3	LD	12.0	48.0	40.0	8.0	39.0	46.0	6.0	355	79	11	20.5		MB
3	LD	22.0	42.0	36.0	6.0	36.0	47.0	11.0	356	79	11	22.0		MB
3	LD	13.0	48.0	39.0	6.0	32.0	53.0	9.0	357	79	11	23.8		MB
3	LD	8.0	43.0	49.0	6.0	37.0	43.0	14.0	358	79	11	24.7		MB
3	LD	9.0	48.0	42.0	2.0	32.0	54.0	12.0	359	79	11	26.5		MB
3	LD	31.0	26.0	43.0	9.0	40.0	43.0	8.0	360	79	11	27.0		MB
3	LD	12.0	49.0	40.0	5.0	36.0	53.0	6.0	370	79	14	17.0		MB
3	LD	9.0	46.0	45.0	12.0	39.0	45.0	3.0	371	79	14	22.0		MB
3	LD	9.0	45.0	46.0	8.0	48.0	36.0	8.0	372	79	14	22.5		MB
3	LD	11.0	45.0	44.0	7.0	41.0	46.0	6.0	400	79	19	13.2		MB
3	LD	19.0	38.0	43.0	9.0	38.0	45.0	9.0	401	79	19	13.9		MB
3	LD?	30.0	33.0	37.0	9.0	43.0	42.0	6.0	84	78	12	9.5		MB?
3	LD?	29.0	33.0	38.0	99.9	99.9	99.9	99.9	85	78	12	10.0		MB?
3	LD?	14.0	52.0	34.0	7.0	28.0	60.0	5.0	86	78	12	11.0		MB?
3	LD?	14.0	51.0	35.0	99.9	99.9	99.9	99.9	87	78	12	12.0		MB?
3	LD?	15.0	37.0	48.0	6.0	35.0	51.0	8.0	391	79	17	.0	A	MB
3	LD?	13.0	48.0	39.0	4.0	34.0	51.0	11.0	392	79	17	.0	B	MB
3	LD?	13.0	48.0	39.0	3.0	35.0	51.0	12.0	393	79	17	.0	C	MB
3	LD?	12.0	46.0	42.0	1.0	34.0	54.0	11.0	394	79	17	.0	D	MB
3	LD?	16.0	44.0	40.0	1.0	31.0	56.0	12.0	395	79	17	.0	E	MB
3	LD?	10.9	50.5	38.7	6.0	39.0	44.0	11.0	562	80	52	.0	U10	MB
3	LD?	15.5	42.0	42.5	6.0	43.0	42.0	10.0	563	80	52	.0	U7	MB
3	LD?	10.1	46.3	43.6	99.9	99.9	99.9	99.9	564	80	52	.0	U7B	MB
3	LD?	99.9	99.9	99.9	8.0	42.0	42.0	8.0	566	80	52	.0	U7BS	MB
3	LD?	.4	83.4	16.3	5.0	37.0	51.0	8.0	569	81	6	10.7		MB
3	ISSD	6.0	46.0	48.0	6.0	28.0	59.0	7.0	12	78	4	11.0		MB
3	ISSD	6.0	46.0	48.0	99.9	99.9	99.9	99.9	13	78	4	11.0		MB
3	ISSD	7.0	62.0	31.0	3.0	33.0	55.0	9.0	14	78	4	11.1		MB
3	ISSD	23.0	37.0	40.0	18.0	33.0	48.0	.0	15	78	4	13.0		MB
3	ISSD	22.0	40.0	38.0	9.0	29.0	54.0	8.0	16	78	4	13.9		MB
3	ISSD	25.0	42.0	33.0	11.0	37.0	47.0	5.0	17	78	4	15.0		MB
3	ISSD	26.0	40.0	34.0	10.0	32.0	54.0	4.0	18	78	4	16.0		MB
3	ISSD	24.0	41.0	35.0	99.9	99.9	99.9	99.9	19	78	4	17.0		MB
3	ISSD	25.0	37.0	38.0	5.0	28.0	61.0	6.0	20	78	4	18.0		MB

FM.K	FACIES	SAND	SILT	CLAY	K	ILL	MONT	CHL	ID	YR.S	SNUM		DEPTH	DMOD	FORMATION
3	ISSD	23.0	38.0	39.0	3.0	26.0	64.0	7.0	21	78	4		19.0		MB
3	ISSD	18.0	43.0	39.0	99.9	99.9	99.9	99.9	330	79	7		3.0	A	MB
3	ISSD	12.0	47.0	41.0	99.9	99.9	99.9	99.9	331	79	7		3.0	B	MB
3	SD-B	36.0	35.0	29.0	15.0	50.0	33.0	2.0	64	78	10		6.0		MB
3	SD-B	31.0	37.0	32.0	11.0	59.0	26.0	5.0	65	78	10		7.0		MB
3	SD-B	20.0	44.0	35.0	99.9	99.9	99.9	99.9	320	79	4		11.0		MB
3	SD-B	12.0	47.0	41.0	99.9	99.9	99.9	99.9	321	79	4		12.0		MB
3	SD-B	32.0	32.0	36.0	99.9	99.9	99.9	99.9	322	79	4		13.0		MB
3	SD-B	11.0	49.0	40.0	99.9	99.9	99.9	99.9	323	79	4		15.0		MB
3	SD-B	11.0	51.0	39.0	99.9	99.9	99.9	99.9	324	79	5		5.0		MB?
3	SD-B	10.0	52.0	38.0	9.0	40.0	41.0	10.0	325	79	5		6.0		MB?
3	SD-B	13.0	47.0	40.0	99.9	99.9	99.9	99.9	326	79	5		7.0		MB?
3	SD-B	28.0	37.0	35.0	11.0	41.0	43.0	5.0	368	79	14		14.0		MB
3	SD-B	18.0	38.0	45.0	8.0	35.0	48.0	9.0	369	79	14		16.0		MB
3	SD-B?	27.0	38.0	35.0	20.0	53.0	24.0	3.0	68	78	10		10.0		MB
3	SD-B?	21.0	36.0	43.0	20.0	47.0	30.0	3.0	69	78	10		11.0		MB
3	SD-B?	31.0	36.0	33.0	15.0	54.0	26.0	4.0	70	78	10		12.0		MB
3	SD-B?	33.0	35.0	32.0	19.0	48.0	30.0	3.0	71	78	10		13.0		MB
3	SD-B?	21.0	48.0	31.0	18.0	49.0	31.0	3.0	73	78	10		13.5		MB
3	SD-B?	18.0	52.0	30.0	18.0	48.0	31.0	3.0	74	78	10		14.0		MB
3	SD-L	41.0	30.0	29.0	14.0	31.0	50.0	5.0	59	78	9		12.0		MB
3	SD-L	22.0	38.0	41.0	99.9	99.9	99.9	99.9	332	79	7		5.0	A	MB
3	SD-L	22.0	35.0	42.0	99.9	99.9	99.9	99.9	333	79	7		5.0	B	MB
3	SD-L	24.0	40.0	36.0	7.0	37.0	49.0	7.0	352	79	11		15.5		MB
3	SD-L	28.0	40.0	32.0	7.0	42.0	45.0	6.0	353	79	11		17.5		MB
3	SD-L	24.0	38.0	39.0	3.0	40.0	42.0	14.0	364	79	11	A	18.8		MB
3	U	17.0	51.0	32.0	99.9	99.9	99.9	99.9	34	78	5		8.0		MB
3	U	16.0	39.0	45.0	7.0	46.0	35.0	12.0	35	78	5		28.0		MB
3	U	14.0	59.0	27.0	11.0	32.0	51.0	6.0	75	78	11		1.3		MB
3	U	15.0	55.0	30.0	6.0	62.0	27.0	5.0	76	78	11		2.0		MB
3	U	14.0	56.0	30.0	13.0	32.0	50.0	4.0	77	78	11		3.0		MB
3	U	30.0	36.0	34.0	9.0	38.0	46.0	7.0	78	78	11		6.0		MB
3	U	28.0	35.0	37.0	15.0	36.0	45.0	5.0	79	78	11		7.0		MB
3	U	99.9	99.9	99.9	4.0	39.0	46.0	12.0	113	78	13		17.3		MB
3	U	25.0	36.0	39.0	9.0	37.0	43.0	11.0	354	79	11		20.0		MB
3	U	26.0	29.0	45.0	9.0	41.0	38.0	12.0	361	79	11		29.4		MB
3	U	99.9	99.9	99.9	5.0	45.0	30.0	19.0	362	79	11		31.2		MB
3	U	11.0	44.0	45.0	7.0	32.0	53.0	8.0	363	79	11		31.5		MB
3	U	14.0	43.0	43.0	9.0	41.0	44.0	7.0	397	79	19		8.0		MB
3	U	12.0	41.0	47.0	6.0	39.0	46.0	8.0	398	79	19		10.5		MB
3	U	10.0	47.0	44.0	7.0	36.0	48.0	8.0	399	79	19		11.4		MB
3	U	36.0	24.0	40.0	99.9	99.9	99.9	99.9	410	79	21		.0	A	MB
3	U	22.0	35.0	44.0	99.9	99.9	99.9	99.9	411	79	21		.0	B	MB
4	LD?	37.0	32.0	31.0	4.0	29.0	60.0	7.0	80	78	12		5.0		UB?
4	LD?	38.0	32.0	30.0	8.0	28.0	59.0	5.0	81	78	12		6.0		UB?
4	LD?	37.0	32.0	31.0	6.0	28.0	59.0	6.0	82	78	12		7.0		UB?
4	LD?	36.0	34.0	30.0	10.0	30.0	56.0	4.0	83	78	12		8.0		UB?
4	UD	37.0	36.0	27.0	3.0	28.0	58.0	11.0	9	78	4		1.5		UB
4	UD	38.0	35.0	27.0	10.0	30.0	55.0	5.0	10	78	4		4.5		UB
4	UD	40.0	32.0	28.0	12.0	26.0	56.0	6.0	11	78	4		5.9		UB
4	UD	99.9	99.9	99.9	8.0	28.0	60.0	4.0	31	78	4	A	1.4		UB
4	UD	37.0	36.0	27.0	14.0	44.0	34.0	7.0	32	78	5		2.0		UB
4	UD	33.0	38.0	29.0	12.0	47.0	29.0	12.0	33	78	5		6.0		UB

FM.K	FACIES	SAND	SILT	CLAY	K	ILL	MONT	CHL	ID	YR.S	SNUM	DEPTH	DMOD	FORMATION
4	UD	41.0	33.0	26.0	7.0	31.0	57.0	5.0	53	78	9	6.0		UB
4	UD	41.0	33.0	26.0	18.0	36.0	45.0	.0	54	78	9	7.0		UB
4	UD	40.0	32.0	28.0	14.0	29.0	50.0	7.0	55	78	9	8.0		UB
4	UD	39.0	33.0	28.0	12.0	39.0	45.0	5.0	56	78	9	9.0		UB
4	UD	40.0	33.0	27.0	10.0	35.0	53.0	2.0	57	78	9	10.0		UB
4	UD	40.0	33.0	27.0	10.0	32.0	48.0	9.0	58	78	9	11.0		UB
4	UD	34.0	35.0	31.0	99.9	99.9	99.9	99.9	101	78	13	1.5		UB
4	UD	34.0	34.0	32.0	8.0	27.0	60.0	5.0	102	78	13	2.5		UB
4	UD	35.0	35.0	30.0	9.0	34.0	53.0	4.0	104	78	13	3.5		UB
4	UD	36.0	36.0	28.0	6.0	28.0	61.0	5.0	105	78	13	4.5		UB
4	UD	42.0	33.0	26.0	9.0	37.0	48.0	6.0	350	79	11	9.0		UB
4	UD	30.0	42.0	29.0	6.0	38.0	45.0	11.0	351	79	11	12.0		UB
4	UD	41.0	34.0	26.0	17.0	40.0	43.0	.0	396	79	17	.0	F	UB
4	UD	34.0	37.7	28.3	11.0	44.0	40.0	6.0	568	81	6	5.9		UB
4	UD	39.1	34.5	26.5	14.0	46.0	36.0	4.0	571	81	13	4.2		UB
4	UD?	36.0	34.0	30.0	10.0	29.0	57.0	4.0	38	78	7	5.0		UB
4	UD?	40.0	33.0	27.0	5.0	23.0	67.0	4.0	43	78	8	6.0		UB
4	UD?	41.0	34.0	25.0	10.0	25.0	58.0	6.0	61	78	10	3.0		UB
4	UD?	40.0	33.0	27.0	12.0	31.0	54.0	2.0	62	78	10	4.0		UB
4	UD?	41.0	30.0	29.0	14.0	42.0	41.0	2.0	63	78	10	5.0		UB

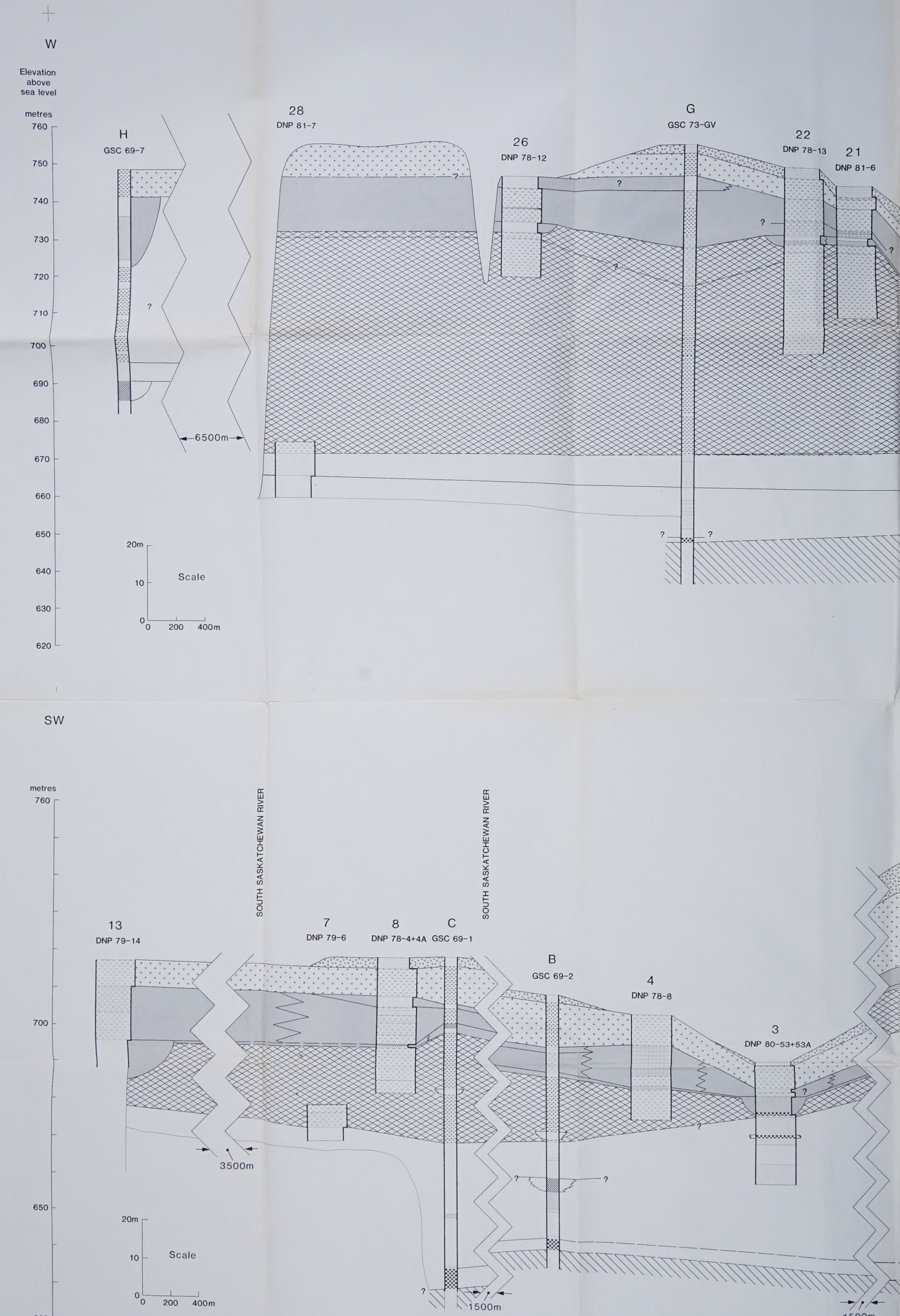
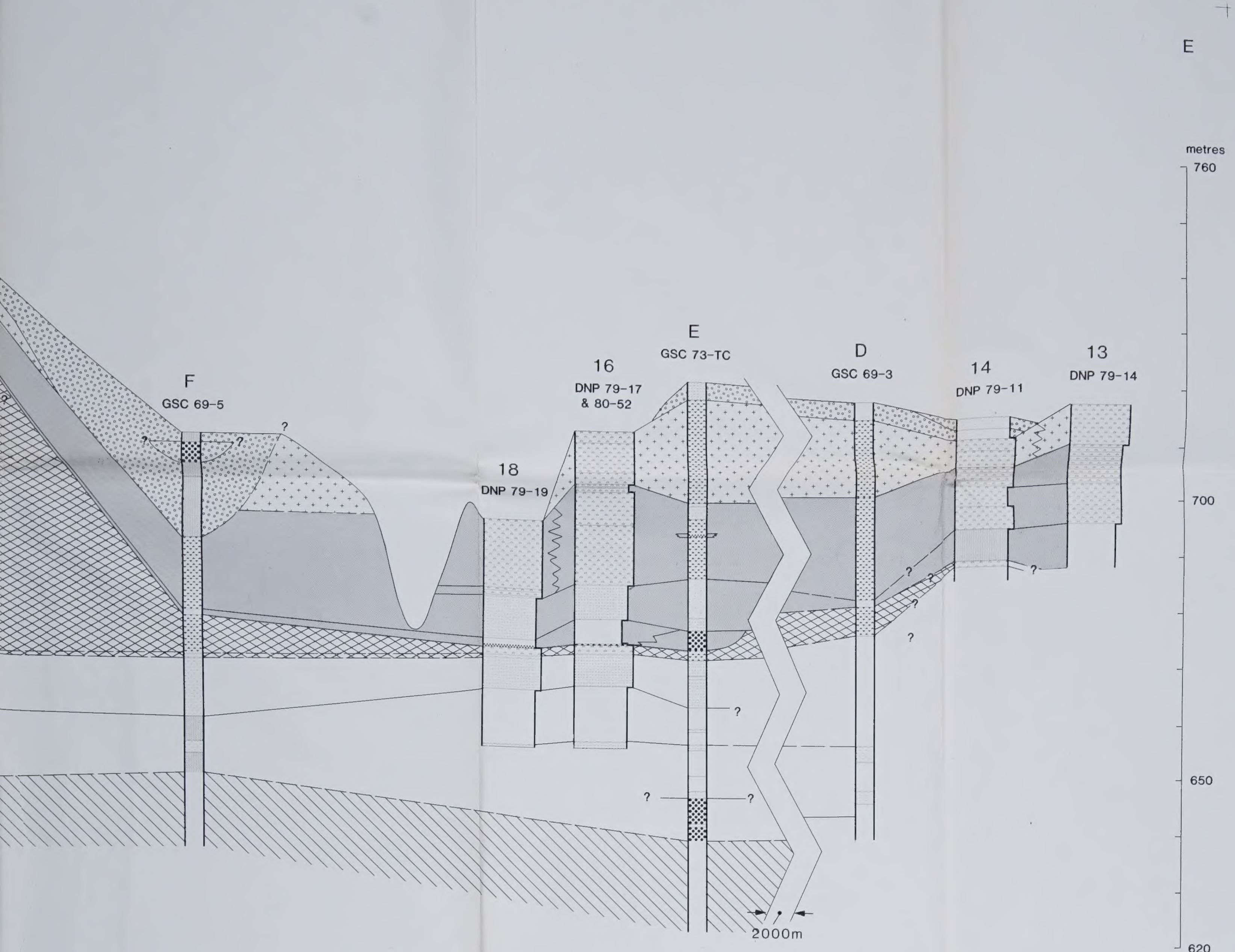
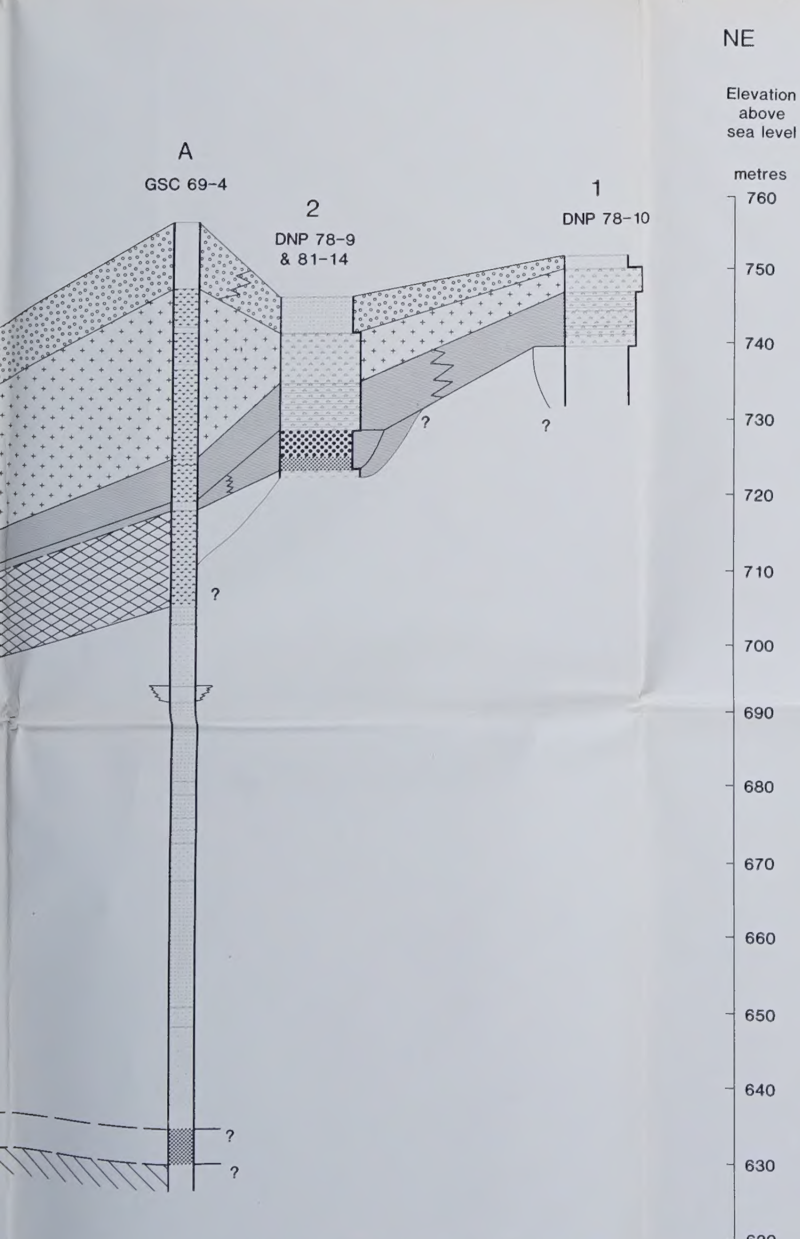


Figure 3.3. Detailed lithostratigraphic cross section of Quaternary sediments in the Medicine Hat area. Lithofacies a
Measured outcrops are designated with a number and outcrops with a letter.





LEGEND

LITHOFACIES

- Diamicton - unlayered
- Diamicton - stratified
- Diamicton - layered and containing lenses
- Interbedded diamicton, sand, and silt
- Diamicton - undifferentiated
- Clay and Silt Rhythmites
- Silt
- Sand
- Gravel - fine
- ? indeterminate correlation
- --- assumed contact

STRATIGRAPHIC UNITS

- formation C
- formation B
- formation A
- Empress Formation
- Upper Cretaceous

are shown schematically where possible (refer to legend).

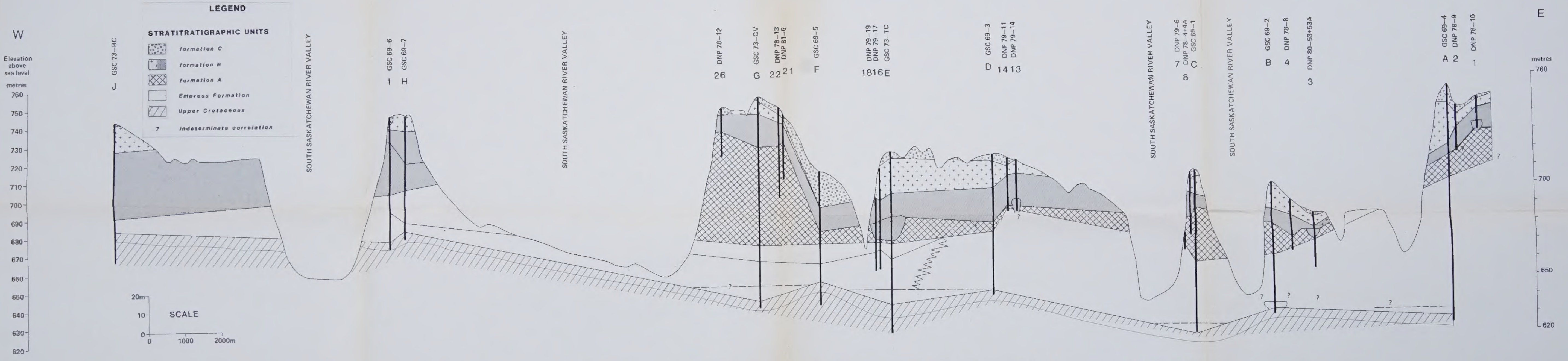


Figure 3.1. Summary cross section showing the relationship between stratigraphic units in the Medicine Hat area. The heavy vertical lines represent control points. The type of control point indicated by the three letter prefix (DNP for measured outcrops, GSC for rotary testholes).